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PROGRESS REPORT

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1.0 INTRODUCTION

This is the 5th quarterly progress report submitted by AERITALIA - GSS (AIT) under contract NAS9-17877 "Tethered Gravity Laboratories Study". This report covers the period from 25 February 1989 through 24 May 1989.

2.0 TECHNICAL STATUS

2.1 WORK ACCOMPLISHED DURING REPORTING PERIOD

During the reporting period, the task 2.0 (Low Gravity Processes Identification) Final Report was sent to NASA-JSC.

The study task 3.0 (Variable Gravity Laboratory) was carried on according to the study schedule.

The new task (Attitude tether Stabilizer) was not initiated due to absence of proper contractual modification. It was decided to limit (July 31, 1989) the validity of AIT technical change proposal TG-EC-AI-001 that was requested by NASA-JSC, prepared by AIT and sent to NASA-JSC on November 28, 1988.

2.1.1 Variable Gravity Laboratory

2.1.1.1 Conceptual Design & Engineering Analysis (AIT)

- a) The mating of the elevator with the tether has been evaluated with reference to the impact on VGL configuration and on tether operations.
- b) Four basic elevator configurations have been analyzed at a conceptual level.
- c) The elevator "slot" configuration was selected according to minimization of operational difficulties and growth capacity criteria.
- d) The way to control the elevator motion on the tether was analyzed in terms of suitable actuator (Jet, Electromagnetic, Mechanism).
- e) The mechanic solution was preferred and possible options were characterized (Robotic, Wheels, Cog Belt).
- f) A wheel system was finally selected and conceptually designed.
- g) See APPENDIX A for technical discussion of the above points.

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2.1.1.2 Control Strategies (SAO)

- a) Fast Crawling Maneuvers (FCM) have been investigated. Specifically crawling maneuvers with time constants shorter than those used in previous analysis when librational/lateral dampers are activated.
- b) The analysis of the main perturbations acting on board VGL has been started. A Fourier analysis of the acceleration components on board the Elevator has been carried out.
- c) The effect of perturbations, transmitted through the tethers by the Station, upon the acceleration level on board the Elevator has been analyzed analytically.
- d) See APPENDIX B for the complete technical reporting.

2.1.1.3 Technology Requirements (AIT)

- a) The VGL accelerometers problem was defined.
- b) Requirements imposed by scientific experiments were reviewed.
- c) Perturbing accelerations during VGL mission were analyzed in terms of amplitude and frequency.
- d) Preliminary accelerometers requirements were defined for any measurement axis.
- e) See Appendix A for detailed technical discussion.

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2.2 WORK PLANNED FOR THE NEXT REPORTING PERIOD

2.2.1 Variable Gravity Laboratory

- a) Conceptual Design (AIT)
Thermal control and payload area topics will be analysed. The VGL conceptual configuration will be designed.
- b) Control Strategies (SAO)
The analysis of the acceleration acting on board VGL will be continued.
A preliminary geometric design of VGL will be used to run numerical simulations with the rotational dynamics of the elevator.
- c) Technology Requirements (AIT)
Existing accelerometers will be reviewed and compliance with VGL requirements will be assessed.

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3.0 SCHEDULE ASSESSMENT

During this reporting period the planned activities shown on the attached schedule have been performed as follows:

ACTIVE C.o.G. CONTROL

- All activities relevant this task are completed.

Low Gravity Processes Identification

- Completed 100%.

Variable Gravity Laboratory

- Concept Design & Engineering Analysis is in progress 90% completed.
- Technology Requirements is in progress 20% completed.
- Control strategies is in progress 60% completed.

The activities control strategies and technology requirements relevant to the Active C.o.G. Control task have not been started, as agreed between Aeritalia and NASA-JSC.

The schedule with the new planning will be introduced if proper contractual modification is signed by July 31, 1989.

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4.0 PROBLEMS AND CONCERNS

After the status review that was held on October 25 at SAO (Cambridge), the following technical/programmatic documents have been sent to NASA-JSC (ATTN. J.W.Alred) by Aeritalia SSG:

1. NOV/28/88 - RSAP/PM/88/169 - Engineering Change Proposal (TG-EC-AI-001) as requested by NASA-JSC (J. ALRED).
2. JAN/16/89 - PCSP/LC/SO/89/012 - Third Quarterly Progress Report (TG-MR-AI-003).
3. FEB/28/89 - RSAP/PM/89/026 - Preliminary Agenda of Mid-Term Review (planned by NASA-JSC for March '89).
4. MAR/23/89 - Telex RSAP/PM/IG/89/035 - Solicitation to Plan Mid-term Review Date.
5. MAR/29/89 - PPVP/LA/GC/89/305 - Fourth Quarterly Progress Report (TG-MR-AI-004).
6. MAR/30/89 - RSAP/PM/89/037 - Task 2 Final Report (TG-RP-AI-001).

Up to now we have not received any formal/informal comment/reply to our technical/programmatic effort. Notwithstanding this situation we have performed all activities according to the study schedule, but we consider as major problem the communication trouble.

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APPENDIX A
VARIABLE GRAVITY LABORATORY

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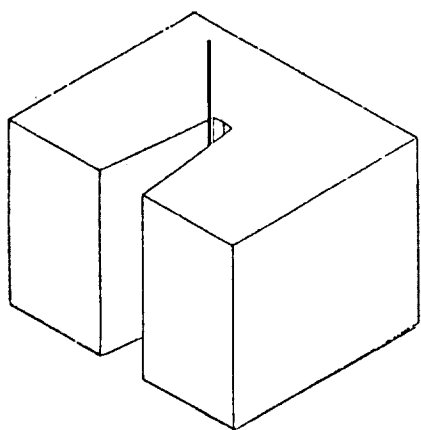
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1.0 TETHER MATING

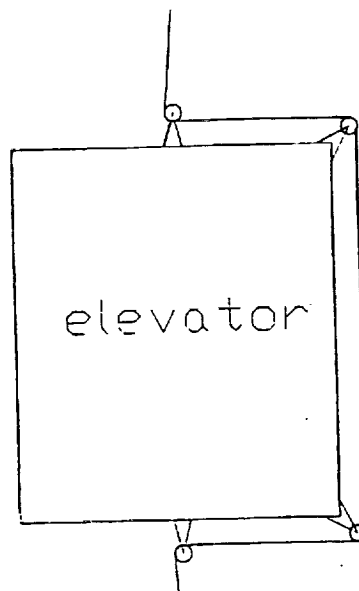
One the most problematic and unique areas of the overall elevator VGL concept is the area regarding the mating of the elevator with the tether. In this section the impact of various conceptual solutions on VGL configurations and on tether operations (deployment and retrieval) will be examined. Four basic elevator configurations (see fig 1.1) will be analyzed at a conceptual level.

In general for the purpose of this discussion it will be assumed that the VGL will be attached to the tether in two points in the "top" and "bottom" locations (this assumption actually does not impact in most of the analysis).

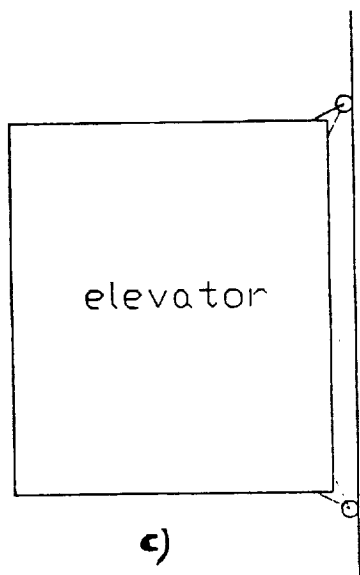
FIG. 1.1 - BASIC ELEVATOR CONFIGURATIONS



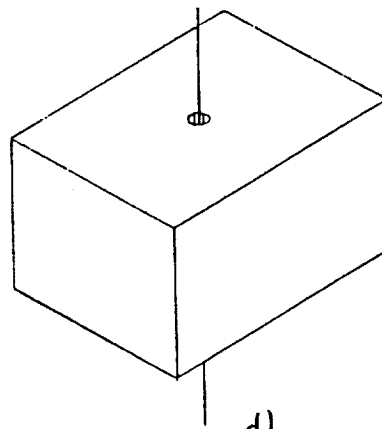
a)



b)



c)



d)

1.1 VGL/TETHER CONFIGURATION

1.1.1 "Slot" configuration

A natural idea for interfacing the tether with the VGL is to use a slot on the VGL through which the tether is introduced (see fig 1.1.a). After tether grappling by the VGL the slot can eventually be closed to increase VGL structural stiffness.

In this scenario the ballast is already mounted on the tether which is on its operational location. The VGL is moved near the tether by means of a suitable RMS - like system or using some kind of translation guide.

The advantage of this solution is that it is possible to attach and detach the VGL from the tether without need of tether operations (deployment/retrieval).

In our case, the tether is deployed only for a limited amount of time, and in general the VGL attachment/ detachment is immediately preceded/ followed by tether operation. In this case the basic advantage of a "slot" VGL configuration is not so important.

The drawbacks of this solution are quite clear:

- a) Large impact on the VGL configuration which needs to be cut along a plane throughout its height (dimension along the tether direction).
- b) Difficult manoeuvre required to introduce the tether within the VGL (accurate position and motion are required to avoid damage to the tether).

A solution which is conceptually similar to the slot solution is the two modules solution (fig 1.2). In this case the linkage between the two sides of the slot is kept to a minimum. The two module can eventually be used for different functions ,i.e., with one of them supporting all the service equipment and the other carrying the payloads.

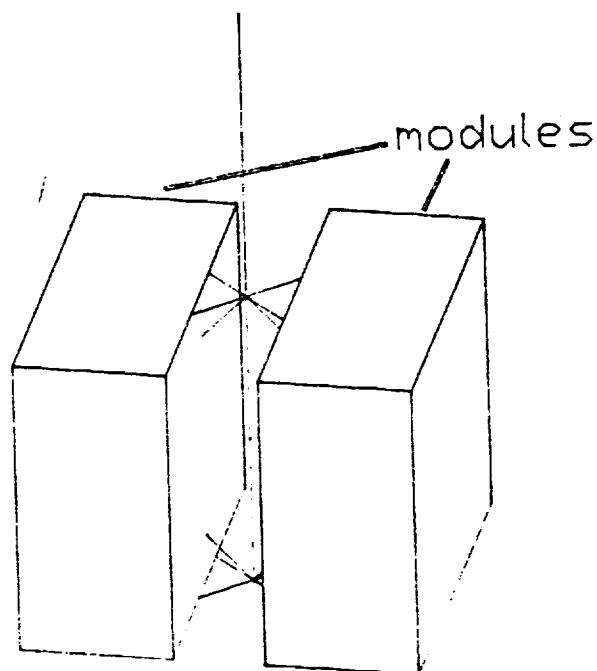
Although attractive in line of principle, in practice there are so many functions (thermal control, OBDH, EPDS) which have to be shared between the two modules that the feasibility of this concept appears doubtful without a large number of connections between them. If ,on the other hand, the modules are required to accomplish the same functions we would end up with a duplication of many equipments without a comparable benefit. Moreover the operational sequence of events present some problems:

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FIG. 1.2 - TWO MODULES CONFIGURATION



- a) If we imagine to connect together the two modules before tether mating the sequence is substantially similar to the basic operational sequence for the generic slot configuration with an added task (connect the two modules).
- b) If first one module and the actuating system are mounted on the tether and then the other one is connected, the problem is somewhat different. The request for complex and critical connections between the two modules in a limited working space relies heavily on the hypothesis of direct human intervention (possibly EVA) which is one of the most precious and scarce resources on the Space Station.

1.1.2 Shaped tether configuration

It is conceivable that instead of having a straight tether going through the VGL, we use a tether going around the VGL keeping the VGL center of mass along the projection of the tether line (fig 1.1.b).

This greatly simplifies the VGL design but worsens the situation for the tether. In particular the introduction of the tether, if in tension, is much more complex and of doubtful feasibility. Moreover it is easy to see that with a tether of respectable diameter as the our one (10 mm diameter) we can likely cause large stresses in the tether fabric.

If the tether is not in tension this means that the tether is not deployed at the moment of tether attachment and in this case other solutions (which will be analyzed in the following pages) appear more promising.

Another problem which is unavoidable is the fact that during VGL motion a transversal displacement "wave" will be travelling along the tether superimposed to the one caused by the Coriolis force on the tether.

1.1.3 Unbalanced configuration

It was always assumed in the previous discussion that the VGL center of mass must lie on the projection of the tether line. If we remove this constraint the elevator can be simply "appended" on one side to the tether (fig 1.1.c). This again leads to a great simplification of the VGL design.

In turn we have a torque around the tether center which has two main consequences:

- a) There are displacements of the two tether portions (after and before elevator) and of the elevator itself such that an equilibrium position is achieved.
- b) The tether (which is a beam) undergoes a substantial stress due to the gravity torque.

Point a): if we assume no stiffness of the tether the VGL and the tether portion between VGL and ballast will position themselves in such a way not to induce any moment with reference to the point of attachment between Space Station and ballast.

The situation is depicted in fig 1.3.

The angle that the longitudinal axis will make with the local vertical will depend on the elevator geometry and on its position along the tether. For increasing VGL distance from Space Station the tension due to remaining portion of the tether (toward the ballast) will decrease while the force acting on the elevator c.o.g. will increase and hence a larger equilibrium angle will result.

In a more precise way

let H = elevator longitudinal dimension
 Y = distance of elevator c.o.g. from tether
 β = $\arctan(Y/(H/2))$
 F = force acting on the elevator = $3 \cdot M_e \cdot N^2 \cdot X_e$
 N = mean orbital rate = 0.00114 rad/sec
 X_e = elevator distance from overall c.o.g.
 X_b = ballast distance from overall c.o.g.
 M_e = elevator mass = 2000 Kg
 M_b = ballast mass = 2200 Kg
 μ = linear tether density = 0.1 Kg/m
 T = tether tension on the point of attachment facing the ballast = $3 \cdot N^2 \cdot [M_b \cdot X_b + 1/2 \cdot \mu \cdot (X_b^2 - X_e^2)]$

It has to be

$$F \cdot Y \cdot \sin(\alpha + \beta) = T \cdot H \cdot \sin(\alpha)$$

α being the required equilibrium angle

FIG. 1.3 - UNBALANCED CONFIGURATION EQUILIBRIUM

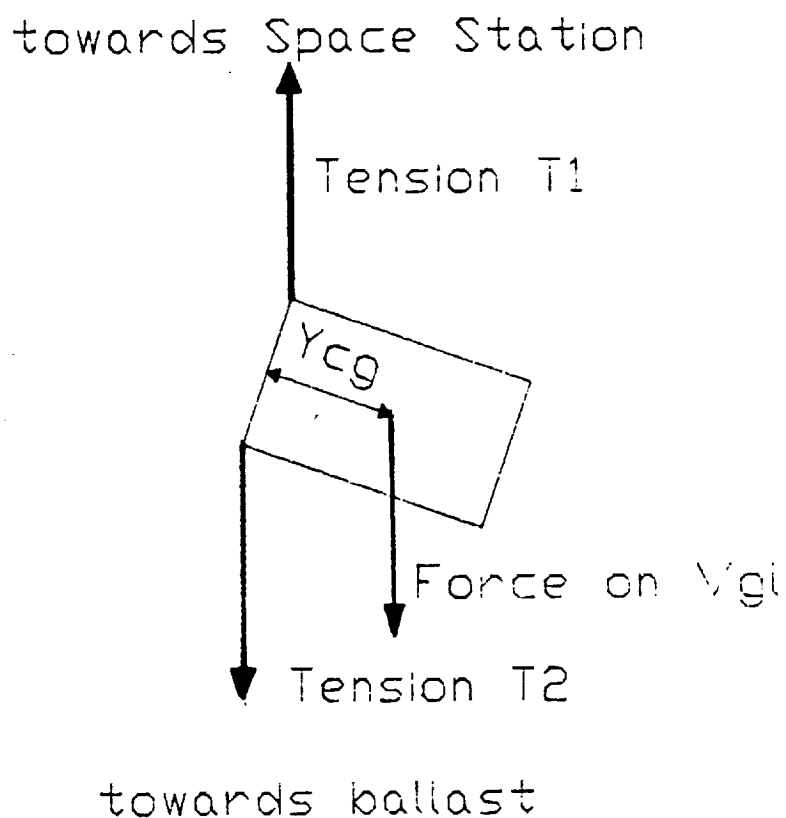
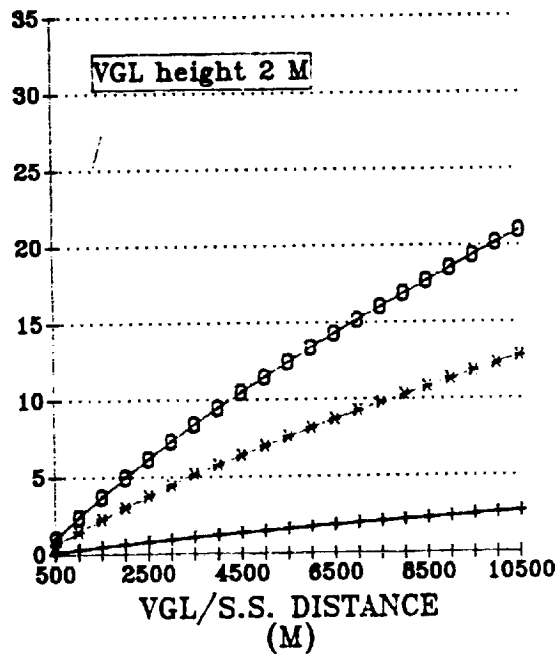
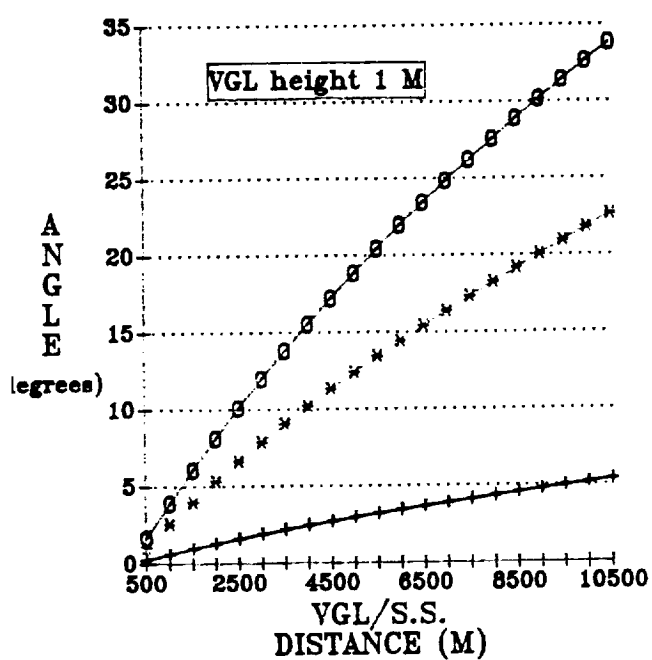


FIG. 1.4 - EQUILIBRIUM ANGLE



angle between VGL longitudinal
axis and local vertical

VGL c.o.g.
distance
from tether

+ 0.1 M * 0.5 M o 0.9 M

In fig. 1.4 the angle made by the local vertical with the longitudinal axis of the elevator is reported. It can be seen that even for comparatively low distance of the VGL c.o.g. from the tether this angle exceeds 10 degrees quite easily. Moreover this angle changes quite quickly with the distance from Space Station, adding a further dynamic effect to the already complex tether environment.

Point b)

For a VGL having its c.o.g. 0.5 m away from the tether (which is a comparatively low value) and 5000 m away from Space Station a torque of approx 20 Nm will result.

For the given size of tether this would result (if there were no tension) in a stress within the tether near to 200 MPa, not far from the maximum admissible stress.

In reality both mechanism (tether tension and transversal stiffness) work towards maintaining the tether in shape and the resulting angle and stresses will be somewhat lower.

The simplification in VGL configuration is relative; in fact the exigency of keeping the VGL c.o.g. as close as possible to one of its sides can lead to important disadvantages as putting the batteries (which are probably the most massive elements) near the tether further reducing the amount of space which can be used for micro-g operation (locations near the tether are the best for low disturbances).

The VGL handling during tether mating can still be faced by problems even if it is simplified with reference to what it is encountered with the "slot" configuration.

1.1.4 Hole configuration

The simplest VGL configuration which can house a tether is one with an hole running throughout its longitudinal dimension. In this way we achieve the lowest impact on the VGL which has merely to keep a cleared zone of some centimetres around the longitudinal axis through its c.o.g. (see fig 1.1.d). No structural weak points or additional constraints on subsystem location are present.

On the other hand it is required that the tether is completely retrieved to attach/detach elevator from it. In a permanent tether scenario this would be probably an unacceptable requirement, but in our case this is something which is not only foreseen, but necessary (both for tether survival and for reducing impact on Space Station micro-g experiments).

The tether will be introduced within the VGL hole using a rigid guide slightly longer than the VGL longitudinal dimension. With the guide protruding from the VGL we can then attach the ballast to the end of this guide. This is much simpler than what is required in the case of the "slot configuration" as it is only required that the VGL is in a certain position within a given error whereas in the other case the whole elevator is required to move (or be moved) following a predetermined path (always with approximately the same error).

Among the various advantages of this configuration over the "slot" one we can cite:

- a) Reduce number of mechanism and operation. In fact no mechanical closure of the slot neither a complex guidance for VGL is required.
- b) Higher structural stiffness expecially around the tether axis. The slot causes the VGL structure to behave as a C shaped beam.
- c) Better thermal coupling within the elevator
- d) For a given elevator size the room left empty for tether operation is kept to a minimum. Notice that the zone near the tether is the one where the best micro g condition are met (low transversal gravity gradient, reduced distance from axis of rotation lowers effect of rotation around tether axis).

Operation sequences of events for this configuration and for the "detachable" ones are reported and commented in the following chapter.

1.2 OPERATIONS

VGL and associated tether operations identification is a fundamental issue in the evaluation of the relative merits of the proposed VGL configurations.

What follows is a notional sequence of events which will take place during normal and emergency (system components malfunctioning) situations. The two configurations which will be compared are the "hole" one and a generic "detachable" configuration which does not require tether operation to be attached/detached from tether. It must be remembered that minor payload/service maintenance operation can be made with the tether still deployed but for most of the times VGL missions will involve the complete sequence of events.

1.2.1 Normal situation.

Deployment "detachable" elevator

1) Attach ballast to tether.

It is assumed here that when tether is not deployed the ballast will be detached and stowed. This is not necessary in general for a "detachable" elevator where, at the end of tether retrieval, the ballast can be simply docked to a proper docking mechanism.

2) Pay out tether (1st phase)

The tether is payed out until the the distance from Space Station to the ballast is the same that the one the elevator is required to have at the start. This reduces the time lag from operation start to experiment start.

3) Attach elevator

4) Pay out tether (last phase)

Another possible operation sequence can involve elevator motion to reach its starting position after a complete tether deployment. Only further operation and dynamics analysis can decisively choose between these two alternatives.

Deployment "hole" configuration

1) Tether/elevator mating

A rigid guide goes through the elevator hole

2) Attach ballast

The ballast is attached immediately near the "hole" elevator possibly on the rigid guide itself. In this way the two bodies (elevator and ballast) will behave as a single one avoiding dynamic instability problems.

3) Pay out tether

The elevator will not move along the tether. Otherwise the tether can be payed out passing through the elevator which is kept docked to the Space Station. Two cases are possible:

- 1 - the tether is payed out passing through the VGL without any contact with it. In this case there is always the risk that tether motions will cause the tether to rub against the walls of the hole.
- 2 - there is contact between the tether and the VGL. If the tether is payed out in this way there is an added uncertainty in the physical variables (length, speed and tension) which have to be controlled during tether deployment that is due to the interaction between tether and VGL. Another issue is the fact that the maximum deployment rate can be larger than the maximum speed the elevator is required to move. In this case there would be the risk of overloading VGL actuators.

4) Move elevator

The elevator is moved from its position near the ballast to its start position.

Notice the the "detachable" elevator can perform the same operational sequence that the "hole" elevator can do. The reverse is not true.

The operations sequence for retrieval are almost the same executed in reverse order:

Retrieval "detachable" elevator

1) Move elevator

The elevator is moved near the Station at its docking point. This is to be done first, as in this way the elevator will not undergo in this way the risks related to tether retrieval manoeuvre.

2) Detach elevator

3) Retrieve tether

4) Detach ballast

Retrieval "hole" elevator

1) Move elevator

The elevator is moved near the ballast for the same reasons which apply to deployment.

2) Retrieve tether

3) Detach ballast

4) Detach elevator

In general it can be said that the operation sequence for the "hole" elevator are more cumbersome than those for the detachable elevators.

1.2.2 Emergency Situation

It is assumed that elevator salvage is mandatory. Let us start with the elevator far from the Station on the tether. There are two possible kinds of emergency situations that can be of interest:

Tether reel jammed

Depending on the presence of solar arrays and on the bare minimum power consumptions the VGL may impose a time constraint to its permanence on the tether. So there can be the need to retrieve the elevator without waiting for the reel to be repaired or substituted.

"detachable" elevator operation sequence

- 1) Move elevator near the Station
- 2) Detach elevator
- 3) Repair tether reel

If possible. In the worst possible case (e.g. jamming of the tether reel bearings) the tether can be cut. Even in this case it can be possible to salvage the tether itself and the ballast.

"hole" elevator operation sequence

- 1) Move elevator near the Station
- 2) Perform maintenance operations
Take away payloads, replace batteries (if needed).
- 3) Repair tether reel

The same considerations made for the detachable elevator are valid. There will not be in any case the risk of loss of the elevator as the tether can be cut beyond it.

Elevator jamming

The elevator actuator can be jammed or the tether path within the VGL obstructed. It does not appear meaningful to send a rescue vehicle when it is always possible to carry the elevator on the Station (This is the big advantage of the VGL as a micro-g laboratory over free flyers).

"detachable" elevator operation sequence

- 1) Retrieve tether

The tether is retrieved as much as possible (i.e. up to elevator).

- 2) Detach elevator

If possible.

- 3) Complete tether retrieval

"hole" elevator operation sequence

1) Retrieve elevator

The tether is retrieved as much as possible (i.e. up to elevator).

2) Repair elevator or clear tether path

If possible. In some cases this can not be possible or worthwhile (expecially if something happened in the cavity inside the elevator).

3) Complete tether retrieval

There is not such a large difference between the operation sequences which has to be performed in the two cases even if it is apparent that problem cause by elevator actuators malfunctioning are somewhat more difficult in the case of the "hole" configuration.

1.3

CONCLUSIONS

The process of selection among the various elevator configurations has to evaluate both the problems of the elevator itself and those caused by it on the Space Station hardware and operations.

Even at a first analysis it is evident that the two configurations which can be considered valid competitors are the "slot" and the "hole" one.

In fact:

- a) the "two modules" configuration does not offer any advantage over the "slot" one and has some problems in the field of payload/service sharing between the two modules.
- b) the shaped tether would require additional hardware and the tether would be more difficult to handle with reference either to the "slot" configuration or the "hole" one (tether with or without tension).
- c) the unbalanced configuration shows unacceptable behaviour if (relatively) high g missions are foreseen.

For what regards the "hole" and the "slot" configuration a brief comparisons must say:

- 1) the "slot" configuration has more problems for what attains more specifically to the elevator itself whereas it offers a more straightforward and simple operation sequence.
- 2) the "hole" configuration has no weak points and tether/VGL mating is probably somewhat easier. On the other hand the operations sequence shows that operations themselves would be a big deal more cumbersome and risky.

Notice that certain facets of the operation could well hide unexpected problems. This is the case for the problem of introducing the tether within the elevator in both configurations and for the ballast attachment in the "hole" one. Nevertheless sufficient elements are already present to draw a conclusion.

Our choice for the elevator configuration is the "slot" configuration.

Two main reasons were fundamental to this choice:

- a) In the scenario we are picturing the VGL (initial stage of the Space Station) the most precious resource will probably be the crew time. Choosing the "slot" elevator we trade off VGL design complexity with the operational difficulties.
- b) The potential growth capacity is much larger for the "slot" elevator which can be easily adapted to a more prolonged or semi - permanent tether deployment.

2.0 VGL/TETHER INTERFACE

In this chapter the possible options for the physical interface between VGL and tether will be compared and a preliminary definition will be performed.

2.1 ELEVATOR MOTION ANALYSIS

In the analyses of S.A.O. a baseline "shape" for the elevator motion was found. We have taken that shape and adapted it to the most requiring elevator motion case, that is, the motion from near the ballast to the c.o.g.

The equations defining the motions are:

$$L_C = L'_C * [\tanh(a*t)]^y$$

(for the first phase $t < t_A$)

$$L_C = L'_C * [\tanh(a*t_A)]^y + L''_C * (t - t_A) / (t_B - t_A)$$

(for the second phase $t_A < t < t_B$)

$$L_C = L_{tot} - L'_C * [\tanh(a*(t_{tot} - t))]^y$$

(for the last phase $t > t_B$)

where

L_C = travelled tether length as a function of time t

L'_C = travelled length during the hyperbolic tangent phase

L''_C = travelled length during the constant speed phase

L_{tot} = total travelled length = 10340 meters

t_A = time when the maximum speed is reached

t_B = time at the end of the constant speed phase

t_{tot} = total travel time

y = a "shape" parameter that rules the steepness of the motion. A value of 5 was selected as the best one by S.A.O.

a = time constant (sec^{-1}).

A parametric analysis of the effects of changing the time constant "a" was made to understand which are the required performances of the elevator actuators.

FIG. 2.1 - ELEVATOR DISTANCE

ELEVATOR MOTION

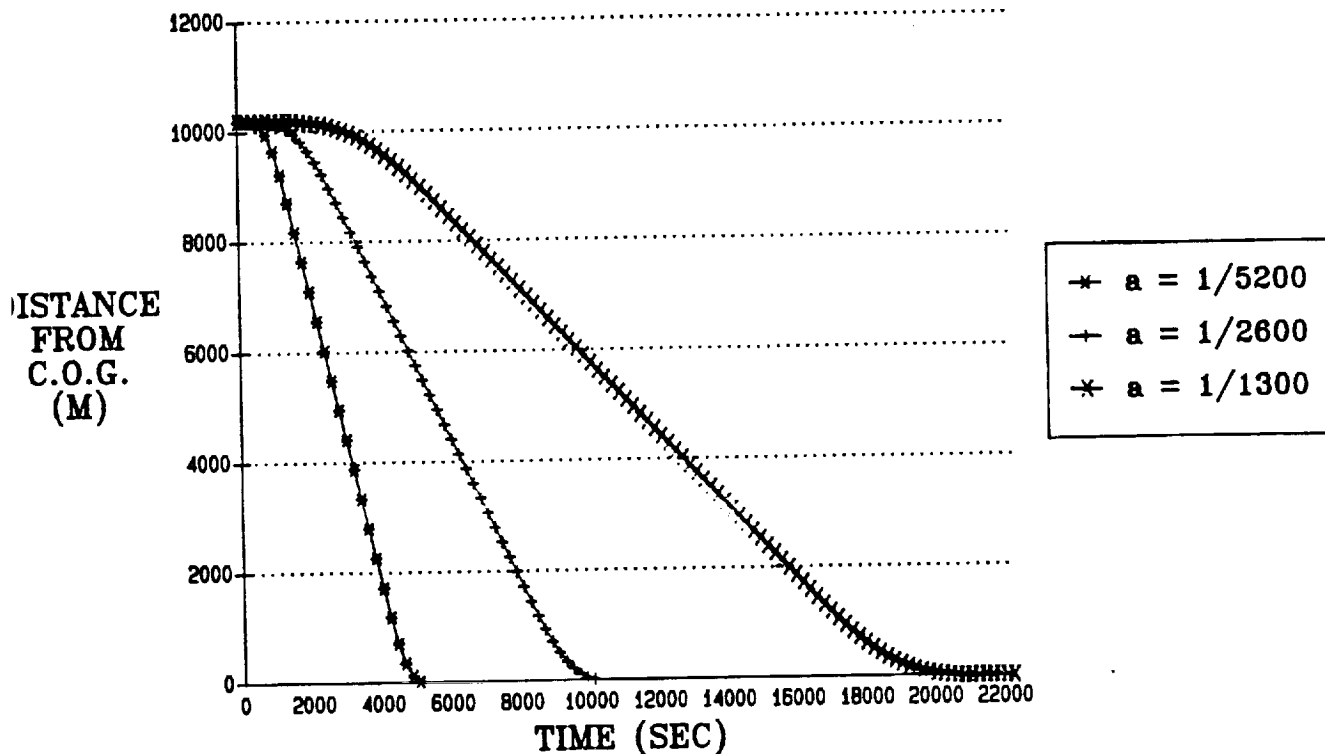


FIG. 2.2 - ELEVATOR SPEED

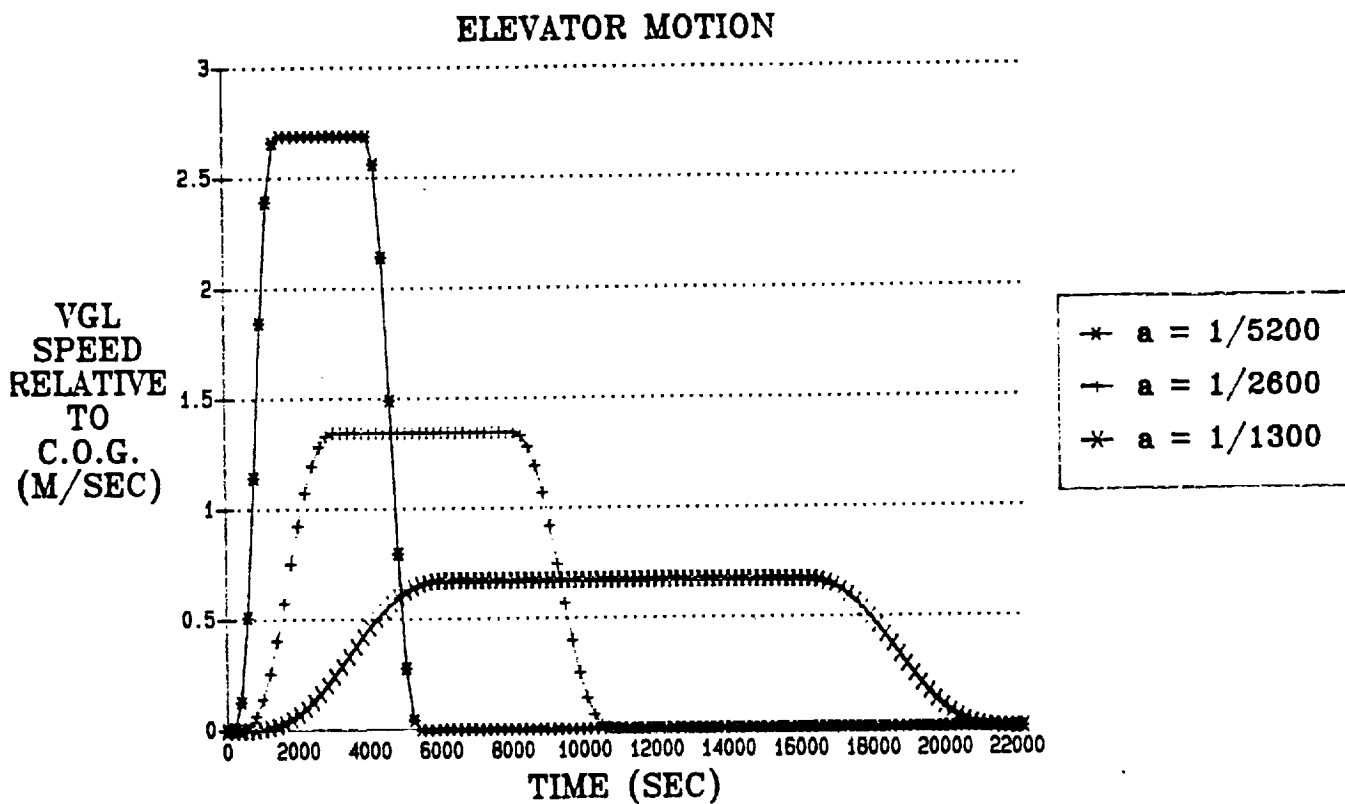
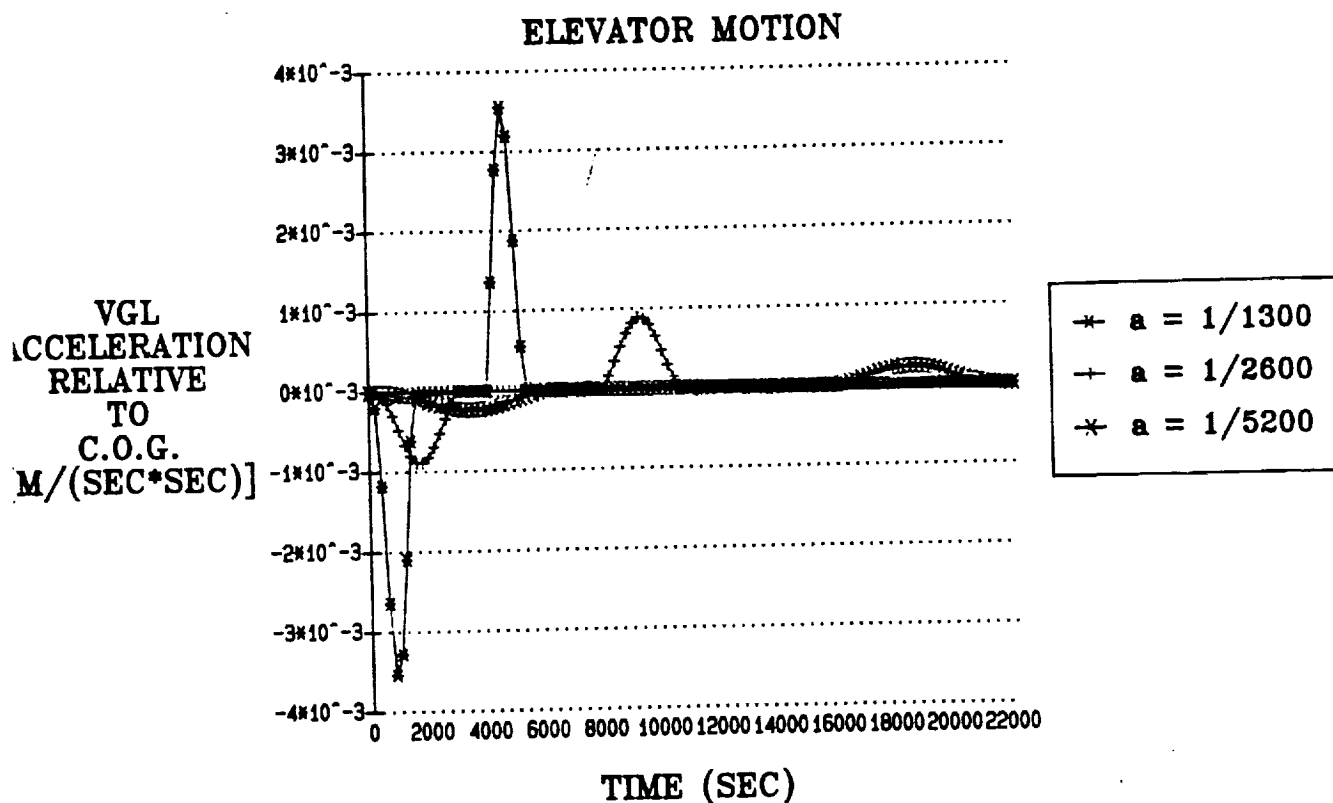


FIG. 2.3 - ELEVATOR ACCELERATION



In fig 2.1, 2.2 and 2.3 the trends of the relative distance, speed and acceleration between the elevator and the Space Station are reported with $a = 1/5200, 1/2600, 1/1300$ sec^{-1} (the choice of this number was dictated by the exigence to cover a significant speed range).

There is a small difference with equivalent plots made by S.A.O. as in their report the travelled length is shown which is something different from what we report as the overall c.o.g. is moving along the tether due to elevator motion. As a first approximation (if we discard terms higher than first degree in the gravity gradient) the overall c.o.g. will not move along the local vertical so the quantity plotted are the "true" values.

From the equation

$$M_e (A_z - 3 N^2 Z) = F_a$$

where

M_e = elevator mass

A_z = acceleration along local vertical (with reference to c.o.g.)

Z = coordinate along local vertical (with reference to c.o.g.)

F_a = actuator force

the actuating force (fig 2.4) and hence the required power can be deduced (see fig 2.5).

FIG. 2.4 - REQUIRED ACTUATING FORCE

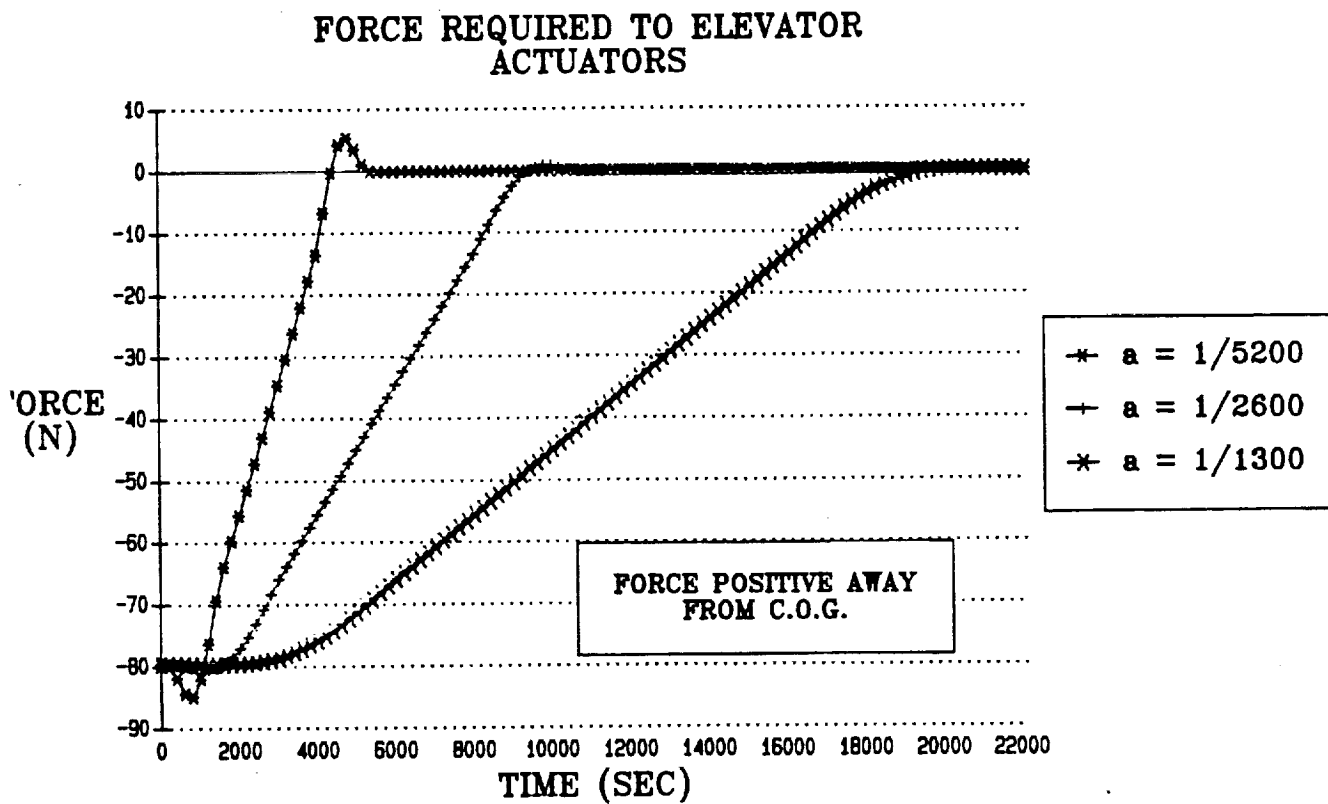
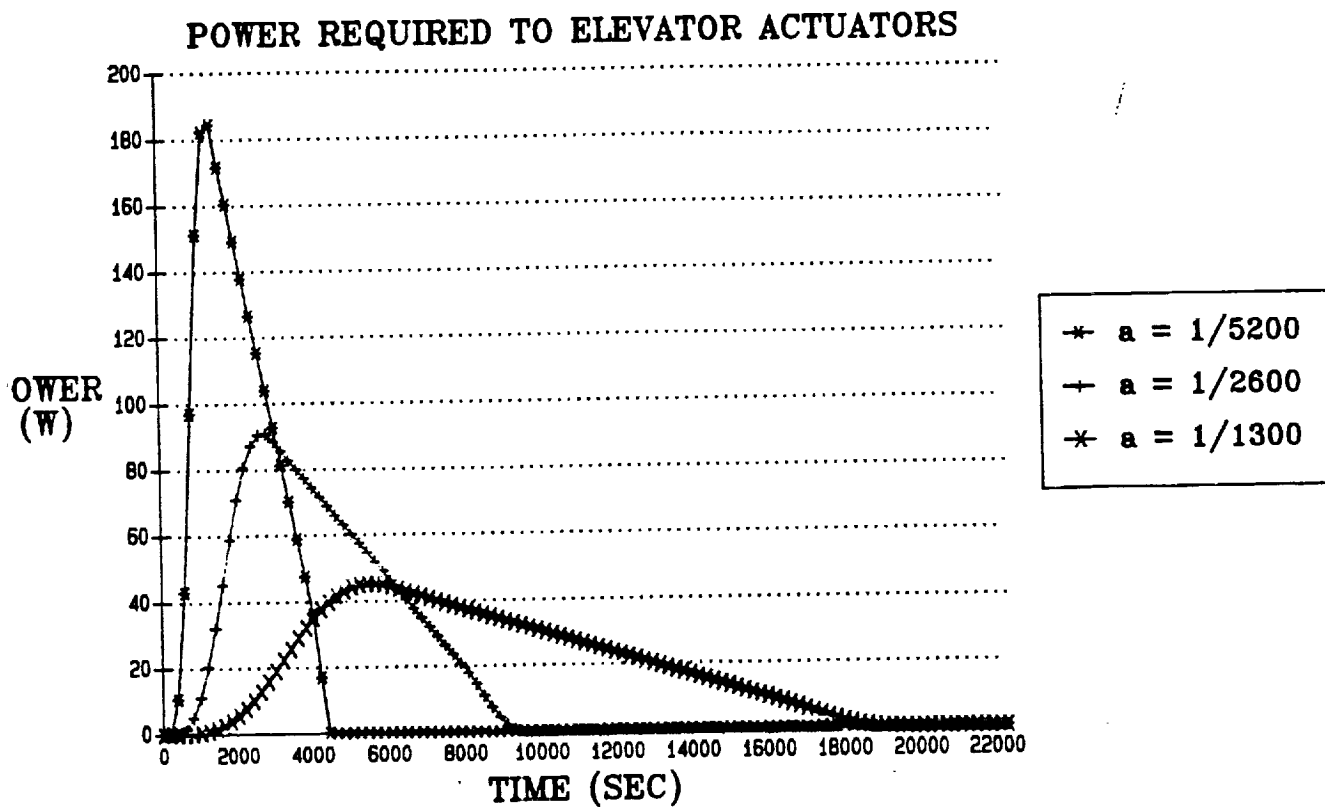


FIG. 2.5 - REQUIRED POWER



Main observations which can be made are:

- 1) The force imparted by the actuators is substantially the one due to the gravity gradient effects; only at the start and at the end of the quickest elevator transfer there is a significant departure of the value of the force from its static value (i.e. from the value dictated by the gravity gradient). In fact the max value of acceleration is approximately 4 mm/sec^2 corresponding to an inertial force of 8 N. This means that the actuator output does not depend (much) on the particular value of "a" chosen.
- 2) The power requirement on the other hand is very much dependant on the value of "a". The quickest elevator motion would require power exceeding 180 W which is most likely an excessive value. Power requirements between 100 and 50 W appear reasonable and would lead to transfer time between 150 and 350 minutes which are still acceptable.

The energy spent in the transfer is the same in all the cases and is of the order of 115 Wh (410000 J).

2.2 ACTUATOR CHOICE

Having a clearer picture of the force and power requirements the motion actuator can be selected. Some kind of mechanical brake will be in any case required to keep the elevator fixed on the station points. This will not be dealt with in this paragraph where the actuators used for elevator motion will be analyzed.

Three are the alternatives which appear sensible:

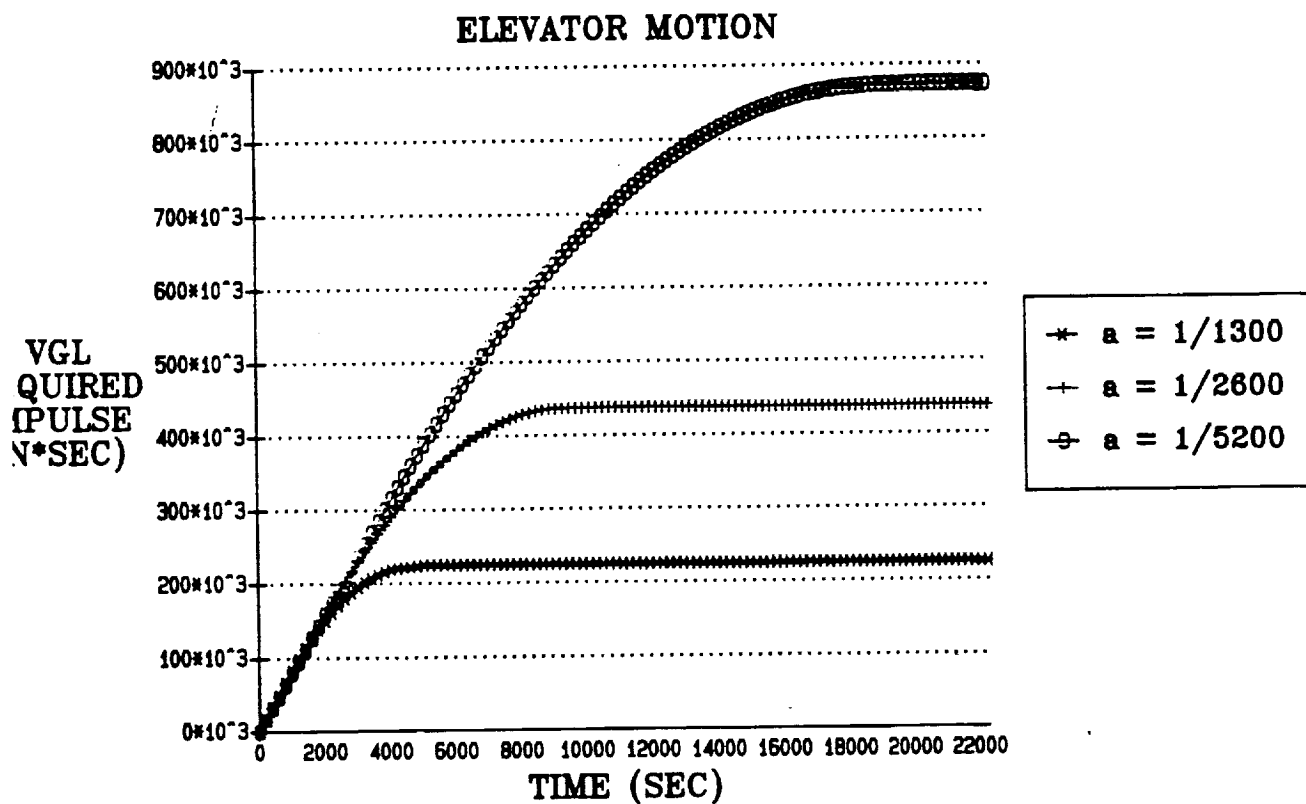
- 1) Jets propulsion
- 2) Electromagnetic propulsion
- 3) Mechanical propulsion

2.2.1 Jets propulsion

The normal way of moving things in space is by use of jets. First thing to be evaluated has to be the total impulse which the manoeuvres along the tether require.

The integral of the force along the time gives us the impulse. The results are reported in fig 2.6.

FIG. 2.6 - REQUIRED IMPULSE



The fact that the total impulse depends on the manoeuvre (unlike the total energy) is natural. In fact it possible to act in a non-conservative way even if the field of external forces is conservative (it is sufficient to think to a firing rocket hovering without moving under the action of gravity).

In order to spend the least propellant a quick manoeuvre is required, but this is the manoeuvre causing the biggest disturbance to the tether.

In any case there are two options available for the propellant:

- a) Cold gases. With a specific impulse of 50 to 60 sec the propellant mass required would be of the order of many hundreds of Kg so this is not a viable options.
- b) Hydrazine. With a specific impulse of 280 to 300 sec the propellant mass can be as low as 75 Kg which would be an acceptable value. The problem with hydrazine is the objective hazards it presents when firing toward the Station and near the tether. In fact the hydrazine thrusters should be placed as near to the c.o.g. as possible to avoid possible unbalance problems due to the thruster misalignments. The effects of hydrazine on tether fabric cannot be established without a clear identification of material but undoubtedly will not be beneficial. Worse than that there will be times when the thruster will be firing toward the Station being near to it and this is scarcely acceptable.

A last point which has to be made is the fact that the location of the overall c.o.g. is an unstable point for the elevator, that is gravity gradient force will push away the elevator from that point unless the elevator is exactly on it (in other words if the elevator were a sphere the c.o.g. location would be the top of an hill). This means that we cannot count on the elevator "falling" on the right point but we have to place it accurately with a mean like thrusters firing which inherently presents problem of finite resolution (for a clearer picture think to the problem of placing a sphere exactly on the top of an hill using rockets).

2.2.2 Electromagnetic propulsion

Conceptually there are some possibilities of exploiting electromagnetic effects to move the elevator along the tether.

These ideas require that the tether is filled with permanent magnets or at the very least with magnetic material. In our scenario of temporary, occasional use of the VGL the cost (both in terms of money and development) and likely fragility of such a tether does not appear consistent with the general underlying VGL design philosophy. Moreover the feasibility itself of these concepts is not clear and the large magnetic field which would be created can be not acceptable under Space Station requirements.

2.2.3 Mechanisms

Here for mechanism we mean the set of all the actuators which, involving direct physical contact between the VGL and the tether, exploit the friction forces to move the elevator along the tether. This is a very broad set with large differences among its components, but some general features can be still be evaluated.

First of all there are two functions which must in any case be accomplished by any kind of actuator and precisely the capability of keeping the VGL in certain position on the tether for long times (up to some weeks) and the capability of keeping the tether at a certain distance from the elevator cavity walls. These two capabilities are inherently present in any kind of mechanical actuator (unlike other system as in the jet propulsion).

Due to the friction forces between tether and elevator there will be always a certain amount of wear in the tether and in the parts of the VGL in contact with it. This can be minimized and a trade off between tether and VGL wear can be made with a proper choice of material.

As the power source will be electrical and carried by the VGL itself, independence from the Space Station is achieved (unlike electromagnetic propulsion systems) and, since the amount of energy spent during transfer is relatively small, the possible elevator travelled length is very large (potentially unlimited if solar arrays are present).

2.2.4 Actuator selection

Mechanism will be used as actuators for the elevator motion.

There is not really a choice to be made among the various alternatives as the jet use is too much penalising in terms of mass and electromagnetic propulsion appears to present a a too large impact on tether configuration and Space Station resources.

The main problem with mechanism will be the reduction of wear (expecially for the tether).

2.3 MECHANISM CHOICE

2.3.1 Robotic

As first example of a possible actuating mechanism a robotic concept was analyzed.

The system under consideration is mainly composed by 2 pincers moved by a worm and internal thread set. Each pincer grasps the tether alternatively during its stroke as shown in fig 2.7.

The pincers are synchronised in order to achieve the smoothest possible motion but sharp variation of the tension on the portion of the tether between the two pincers are almost unavoidable.

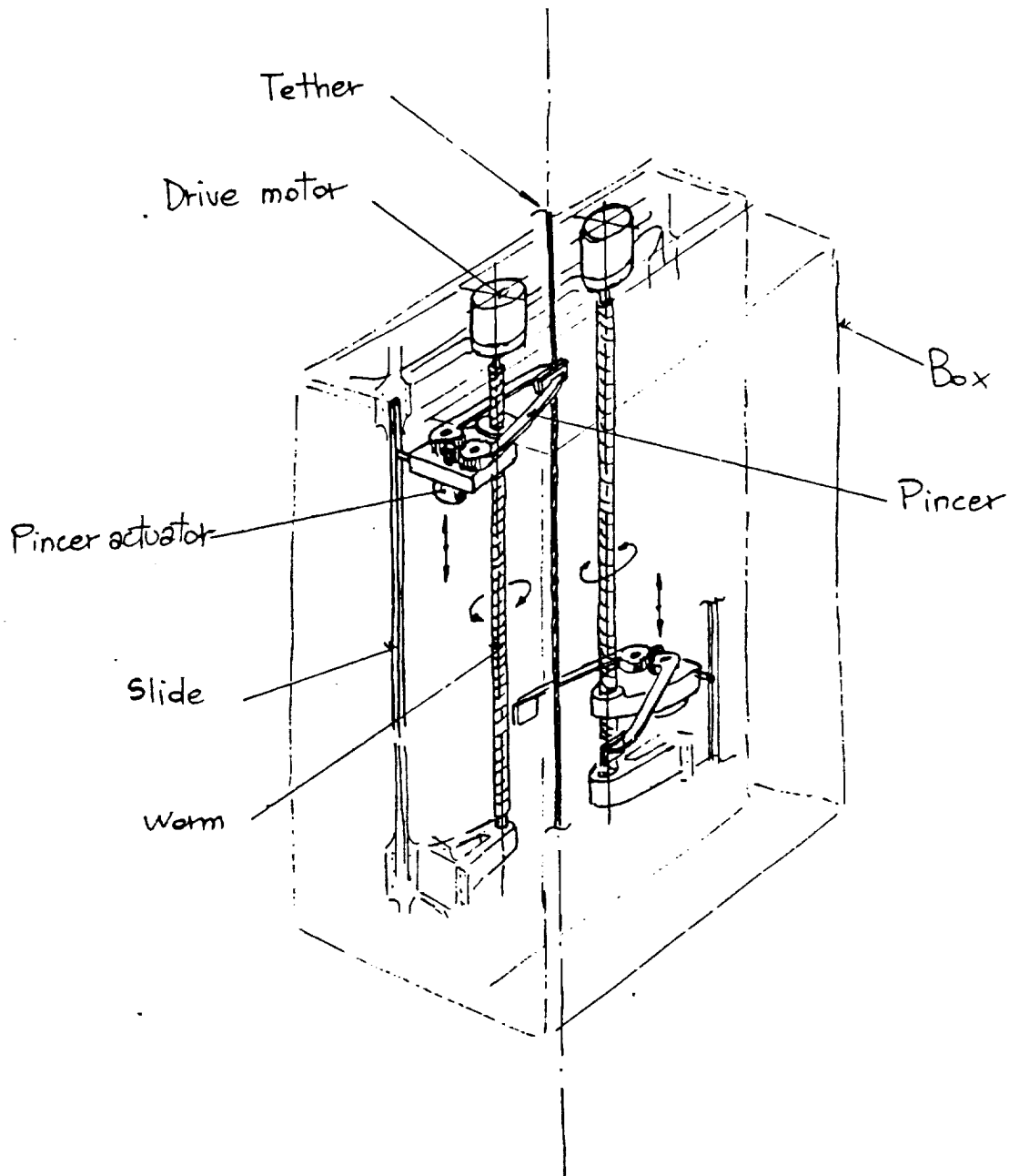
The strong points of this concept are:

- 1) the precision of motion which can be achieved using worm gear
- 2) the mechanism will touch the tether outside the VGL and this should simplify tether mating, mechanism maintenance and in general all the operations which require visual inspection.

The drawbacks are major:

- 1) the motion is any case will have a strong periodic component which will cause disturbances and excite tether longitudinal vibrations
- 2) the complexity of the control system is evident given the requirements on synchronisation.
- 3) even a single failure in tether grappling can lead to dangerous consequences.

FIG. 2.7 - ROBOTIC CONCEPT



2.3.2 Wheels

The simplest idea for moving along the the tether is by using two set of three wheels placed externally at the top and bottom of the elevator. The general idea of this system is given in fig 2.8.

The idea is to have only one motor wheel (only on one set of wheels). This wheel will be the one which is lying in the slot plane. The other set of wheels will act only as a guide for the tether (they exchange forces with the tether only along its radial direction).

At least the motor wheel (but most likely all of them) will be mounted on springs in order to reduce undesired transient loads on the tether due to dimensional imperfections.

Also to reduce the loads on the tether a soft material with high friction coefficient (rubber) will be used to cover the wheels contact surfaces.

On one of the wheels in the set not including the motorized one it will be mounted a brake which will be used during station keeping phase if reduction of the load on the motor wheel is deemed necessary to avoid permanent deformation.

The problems for this system spring from the fact that the contact area is rather small and hence the stresses can be large. If this can be solved, then the simplicity of this solution, the easy access and visibility of the interfaces single out this solution as very interesting.

2.3.3 Cog belts

In order to reduce the localised stresses on the tether the use of cog belts can be examined.

The proposed mechanism uses two cog belts grasping the tether in between; the concept is shown in fig 2.9

In this way we distribute the pressure at the tether/elevator interface.

Referring to the above figure we see that the cog belts are mounted on a triangular pulley and are pressed together by means of sliding blocks. The power is transmitted at the system by means of a worm gear set. This choice guarantees the motion irreversibility.

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FIG. 2.8 - WHEELS CONCEPT

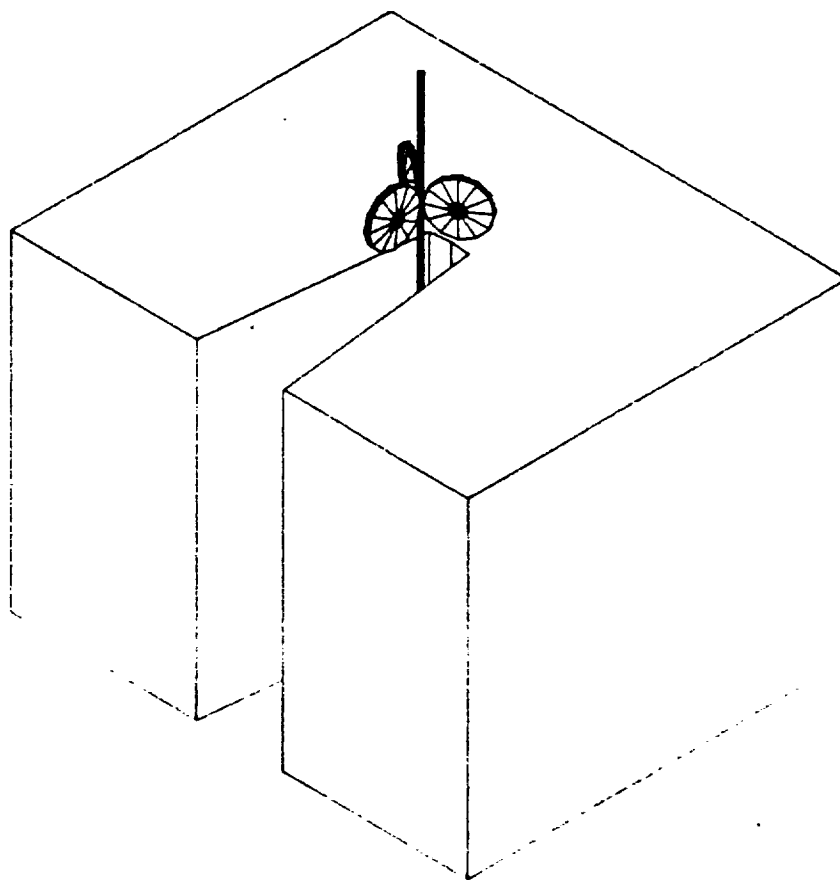
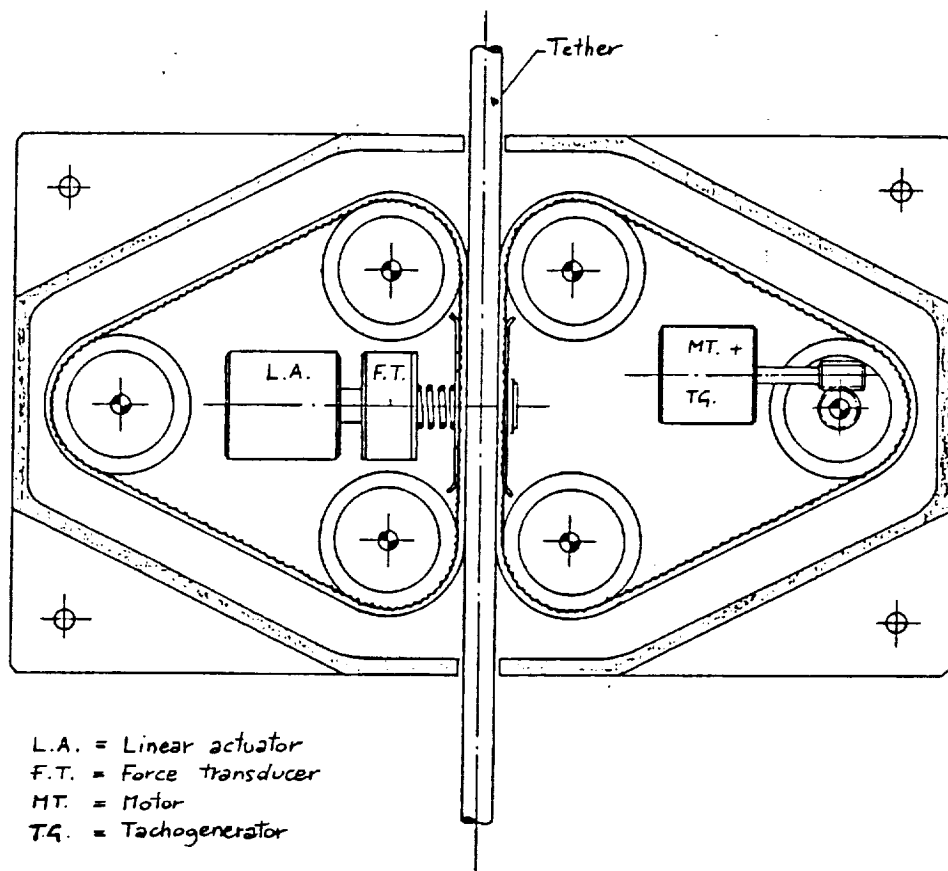


FIG. 2.9 - COG BELTS CONCEPT



There will be two sets of cog belts placed at the top and bottom of the elevator (not in the interior of the VGL cavity to reduce the accessibility and visibility problem).

In general this solution appears to be more complex (think to problem of avoiding tether slipping in the direction outside the plane of the belts) and somewhat less reliable than the wheels.

2.3.4 Mechanism selection

The preferred choice for the mechanism is a wheel system which seems more simple especially for what regards the problem of tether mating. If the problem due to localised stresses cannot be reduced the cog belts are the back up choice. The robotic system involving complex hardware and causing alternative excitation in the tether during a motion which should be as smooth as possible are not really a competitor.

2.4 CAVITY SIZE

The tether will require a certain clearance to avoid rubbing against the wall of the elevator cavity through which it will travel.

The problem lies in finding which is the presumable max displacement of the tether within the VGL under unknown forces which are due to dynamic effects.

An evaluation of order of magnitude of these forces can be done estimating the value of the Coriolis force which will push the elevator along the orbital speed direction. For the range of elevator speed along the tether which is of interest (1 to 2 m/sec) the max force will be

$$F_c = 2 * N * V * M_e$$

where

N = mean orbital rate = $1.14 \cdot 10^{-3} \text{ sec}^{-1}$

V = elevator speed 2 m/sec

M.e = elevator mass = 2000 Kg

F_c = Coriolis force = (approx) = 4.6 N

The max deflection on the tether within the VGL (for a given material and diameter of the tether) depends on:

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- 1) the applied load
- 2) the free suspension span of the tether within the VGL
- 3) the tension in the tether and hence on the position of the elevator along the tether.

Notice that the tension in the tether changes drastically near the contact point(s) of the elevator. In fact if we think to the tension in the tether immediately before the elevator (starting from the c.o.g.), this has to balance the force due to the ballast, the remaining portion of tether and the elevator; whereas the tension immediately after the elevator has to balance the force due to the ballast and the remaining portion of tether only. The dimension of this change in tension can be appreciated examining fig 2.10 where the tension along the tether for various elevator position is reported.

For a quantitative analysis we assume that the elevator has two point of contact with the tether located at its top and bottom but only one of the them is able to exchange forces along the tether axis. Now assuming also that the max acceptable displacement is 0.05 meter which is the force that, if applied on the center of the tether portion within the VGL, would cause such a displacement? The answer is shown in fig 2.11 for different sizes of the VGL and in the two cases for tether attachment (longitudinal loads exchanged in the contact point toward the Space Station or in the contact point toward the ballast).

FIG. 2.10 - TETHER TENSION

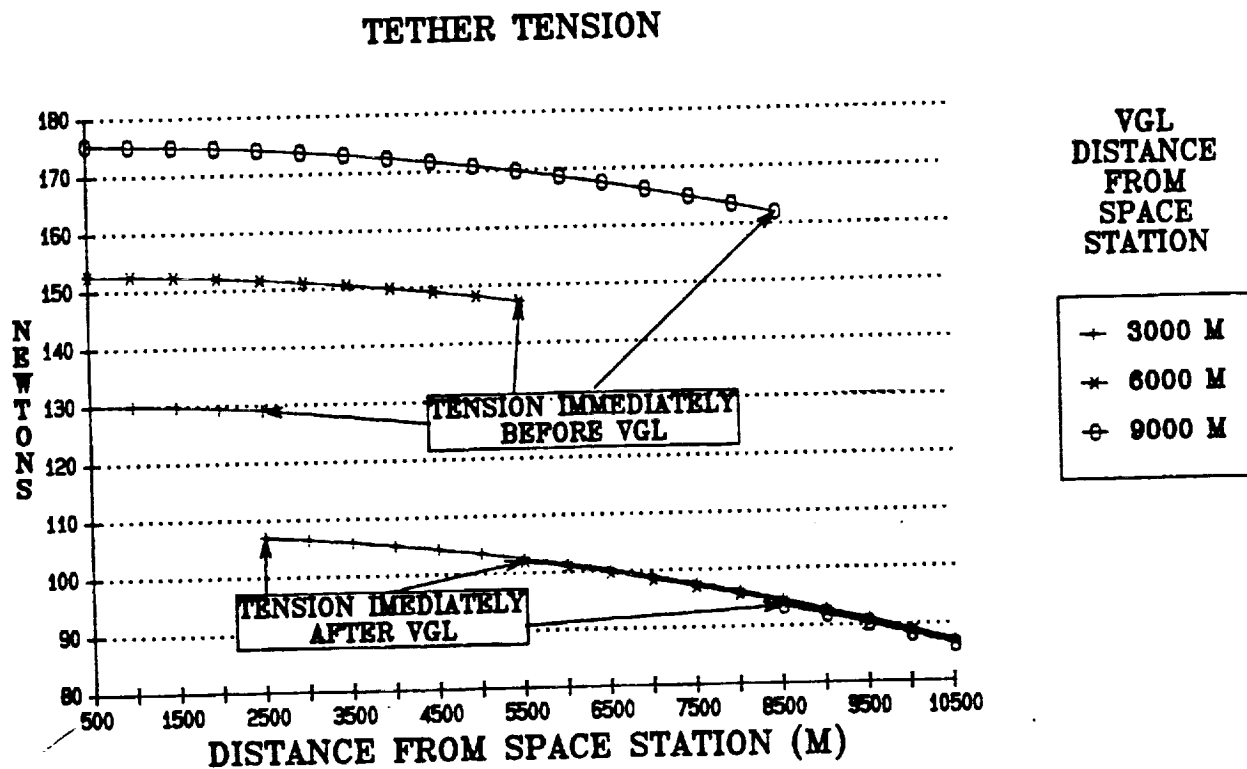
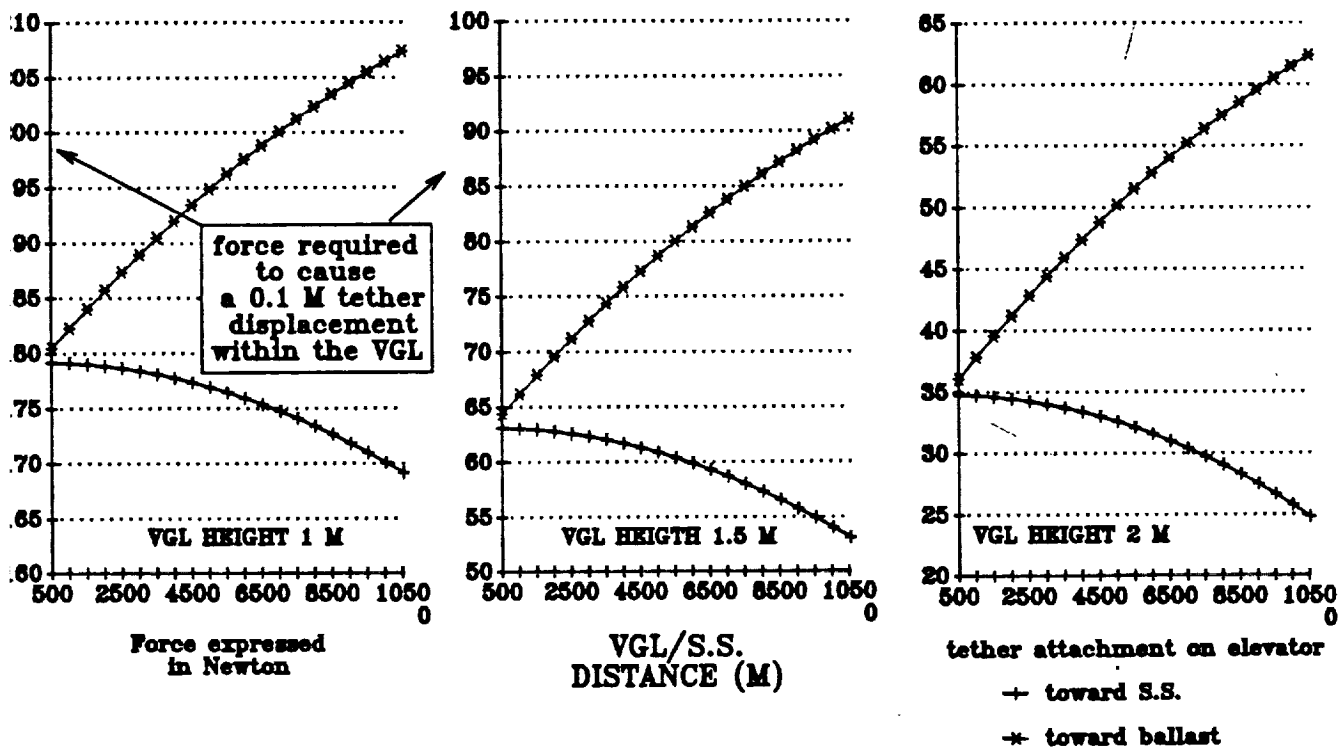


FIG. 2.11 - FORCE REQUIREMENTS



The required loads if there were no tension are:

VGL HEIGHT (M)	LOAD (N)
1.0	82
1.5	25
2.0	10

It can be noticed that the tension give rise to a substantial increase in tether stiffness and that there is a large difference between the values representing different contact modality for the same VGL height (this last was assumed as being equal to the free span of the tether within the elevator).

When the elevator is attached on the contact point toward the ballast the computed force increases as the elevator distance from S.S. increases; that is due to elevator induced tension which is greater the farther the elevator is from the Space Station. On the other hand, if the elevator is attached on the contact point toward the Space Station, the force due to the remaining tether portion is diminishing (there is less tether) and that explains the trend of the graphs.

The indications which can be drawn by the above results are:

- 1) Keep the free span of the tether within the VGL to a minimum.
- 2) Attach the elevator on the tether in such a way to keep the max possible tension within the tether. This is important if relatively large free span of tether are unavoidable.

In any case the computed force is much larger than the max Coriolis force due to elevator motion, so this problem does not appear to be particularly worrisome and the size of the hole would be probably dictated by the operational problems. A diameter of 0.1 M appears to be a sensible minimum value.

3.0 ACCELEROMETERS REQUIREMENTS

Accelerometers will be one of the key sensors for the VLG. During the station-keeping phases of the elevator along the tether, their main function will regard the monitoring of the microgravity level near the payload experiments. When the VGL is moved from one g-level to another one the experiments will be switched off and the accelerometers will be used for supporting the positioning operations of the elevator at the height corresponding to the desired gravity level, and for controlling the damping of the motion-induced transverse and longitudinal acceleration down to the values required for starting the experiments. To date it is not foreseen to use accelerometers as sensors for an automatic feedback control of longitudinal and transverse oscillations of the system.

VGL is designed to provide an almost steady acceleration A_g along the local vertical ranging from 10^{-6} g up to 0.4×10^{-2} g at steps of half an order of magnitude:

10^{-6} , 5×10^{-6} , 10^{-5} , 5×10^{-5} , 10^{-4} , 5×10^{-4} , 10^{-3} , 4×10^{-3} .

These accelerations inside the VGL are achieved by exploiting the effect of gravity gradient, i.e. by placing the VGL at different distances from the C.O.G. along the local vertical by means of a tethered system attached to the Space Station.

The nominal micro-g levels are perturbed by other accelerations related to the VGL orbital and attitude perturbations, tether oscillations, machineries motion on VGL, structural vibrations, and the Space Station perturbations transmitted through the tether.

The source, direction, amplitude and frequency of these disturbances are summarized in table 3.1 (the results relative to the atmospheric drag, and the transverse and longitudinal oscillation refer to the station-keeping at the orbital center).

The actual elevator design doesn't meet completely the requirements imposed by the scientific experiments (ref. LOW GRAVITY PROCESSES IDENTIFICATION, Final Report, February 1989) for the micro-g range. Infact the VGL doesn't allow to explore the acceleration levels above 0.4×10^{-2} g up to 10^{-1} g (to achieve the latter a 250 km long tether is required!).

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Moreover, some problems arise from the requirement of maintaining the residual acceleration vector within a circular cone of 1 degree semi-aperture angle whose axis is along the experiment significant direction.

By considering the perturbing acceleration listed in table 3.1, it can be noted that, even in the case the experiment is mounted with its axis along the acceleration vector resulting from the steady component along the VGL axis, the transverse oscillations of the elevator, and the orbital frequency front acceleration component due to air drag acting on the Space Station and related to the diurnal atmospheric bulge, both cause a periodic oscillation of the acceleration vector whose amplitude is greater than 1 degree for the lowest two g-levels.

Nevertheless this result doesn't mean that one will not be able to fulfil this experimental requirement, by controlling, for instance, the solar panels attitude and by using dampers. In fact the perturbing accelerations during the station keeping were computed with the libration/lateral dampers disactivated, and considering the attitude of the Space Station solar arrays fixed during the whole orbit in a normal position with respect to the orbital velocity (case of maximum drag).

The requirements on the amplitude and dependance on frequency of the modulus of the residual acceleration (see fig. 3.1) are instead practically met also for the lowest micro-g level (fig. 3.2).

acceleration source	acceleration direction (a)	amplitude	frequency [Hz]
gravity gradient	$\pm Y$	$1.3 \times 10^{-1} \mu g$ (b)	dc
residual eccentricity	$\pm Z$ $\pm X$ $\pm Y$	$3.3 \times 10^{-3} a$ (c) $6.7 \times 10^{-4} a$ $3.9 \times 10^{-4} \mu g$	1.8×10^{-4} 1.8×10^{-4} 1.8×10^{-4}
Earth oblateness	$+ Z$ $\pm X$ $\pm Y$	$4.0 \times 10^{-3} a$ $3.0 \times 10^{-4} a$ $4.7 \times 10^{-4} \mu g$	3.6×10^{-4} 3.6×10^{-4} 3.6×10^{-4}
atmospheric drag	$+ X$ $+ X$ $\pm Y$	$4.0 \times 10^{-1} \mu g$ $1.5 \times 10^{-1} \mu g$ $2.0 \times 10^{-4} \mu g$	dc 1.8×10^{-4} 3.6×10^{-4}
transverse oscillations	$\pm X$ $\pm Y$	$1.3 \times 10^{-1} \mu g$ $1.0 \times 10^{-4} \mu g$	3.2×10^{-3} 3.0×10^{-3}
longitudinal oscillations	$\pm Z$	$2.5 \times 10^{-2} \mu g$ (d)	3.0×10^{-3}
VGL attitude motion	$\pm Z$ $\pm X, \pm Y$	TBD	TBD
machineries motion	$\pm Z$ $\pm X, \pm Y$	TBD	TBD
structural vibrations	$\pm Z$ $\pm X, \pm Y$	TBD	TBD

Table 3.1 - Perturbing accelerations during station-keeping

During the travelling along the tether, in addition to the station-keeping accelerations, the VGL will experiment crawling and Coriolis accelerations, and those due to the longitudinal and tranverse vibrations of the tether induced by the elevator motion itself (see table 3.2).

acceleration source	acceleration direction	amplitude [μg]	frequency [Hz]
crawling acceleration	$\pm Z$	3 70	9.5×10^{-4} (e) 1.7×10^{-4} (f)
Coriolis acceleration	$\pm X$	2 260	2.4×10^{-4} (e) 4.6×10^{-5} (f)
induced (g) transverse oscillations	$\pm X$ $\pm Y$	0.25 (TBV) 3.3 (TBV)	dc 3.6×10^{-3} (f)
induced (g) longitudinal oscillations	$\pm Z$	60 (TBV)	2.0×10^{-4} (f)

Table 2 - Perturbing accelerations during crawling manoeuvres

-
- (a) The direction of the perturbing acceleration is given in a reference frame (X, Y, Z), with the origin at the c.o.m. of the VGL, Z along the local vertical (downward), Y toward the orbit pole, and X completing a right-handed system.
- (b) The values of residual accelerations which depend upon the offset in X, Y, have been computed by assuming $X = Y = 1m$.
- (c) a is the steady acceleration level along the local vertical due to gravity gradient.
- (d) Including two longitudinal dampers in series with the two tether segments.
- (e) "short range" manoeuvre ($1/a = 500$ sec)
- (f) "long range" manoeuvre ($1/a = 2550$ sec)
- (g) With lateral/libration dampers activated.

Based on the previous analysis of the foreseen micro-g environment of the VGL, and on the acceleration monitoring required by the experiments it can be derived the following preliminary accelerometers requirements for any measurement axis:

VGL AXIS	RANGE [g]	FREQUENCY BAND [Hz]	ACCURACY
Z	10^{-7} to 0.5×10^{-2}	dc to 100	10%
X	10^{-7} to 3.0×10^{-4}	dc to 100	10%
Y	10^{-7} to 3.0×10^{-4}	dc to 100	10%

The accelerometer sensibility as function of the frequency f should be constant up to $f = 1$ Hz, and should not exceed a linear increase in the range 1 - 100 Hz.

The range, band width, and accuracy (in both real and post real time) are the parameters on which it will be based the first selection of the accelerometers.

In addition the detection mode must allow for zero point corrections, calculation of the resultant acceleration vector and a frequency analysis, the latter being necessary for separating the steady and g-jitter components of the acceleration.

Among all those which will meet the measurement constraints will be then performed a trade-off based on their weight, volume, power consumption, operational temperature range, calibration and thermal/mechanical stabilization time, degree of development and qualification, availability, and costs.

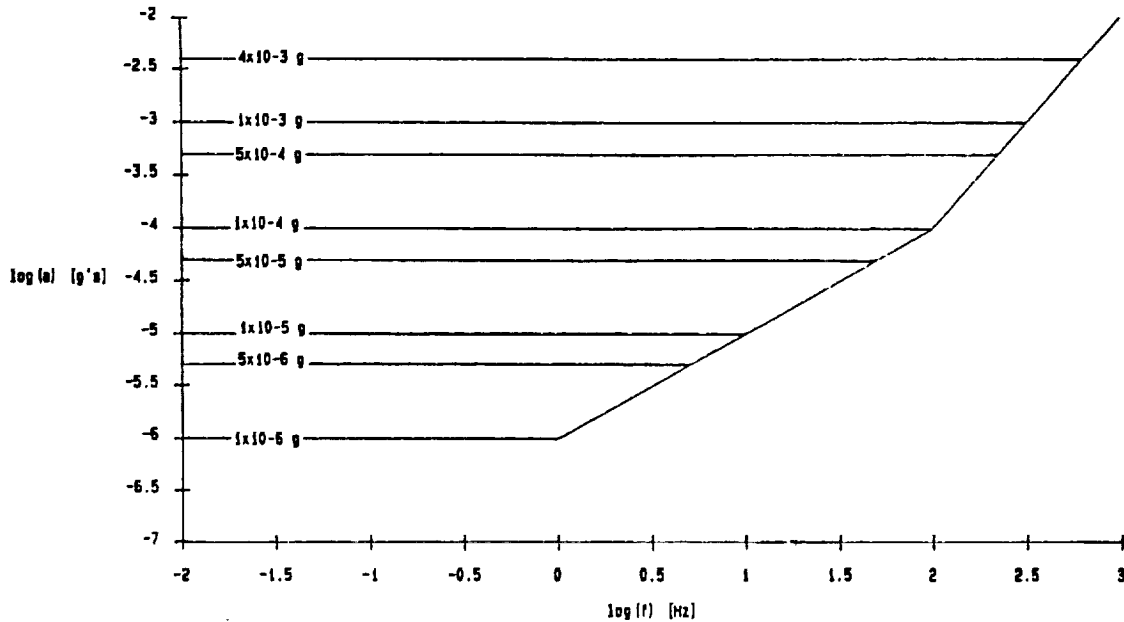


Fig. 3.1 - Residual acceleration modulus dependance on frequency for any g-level: experimental requirement.

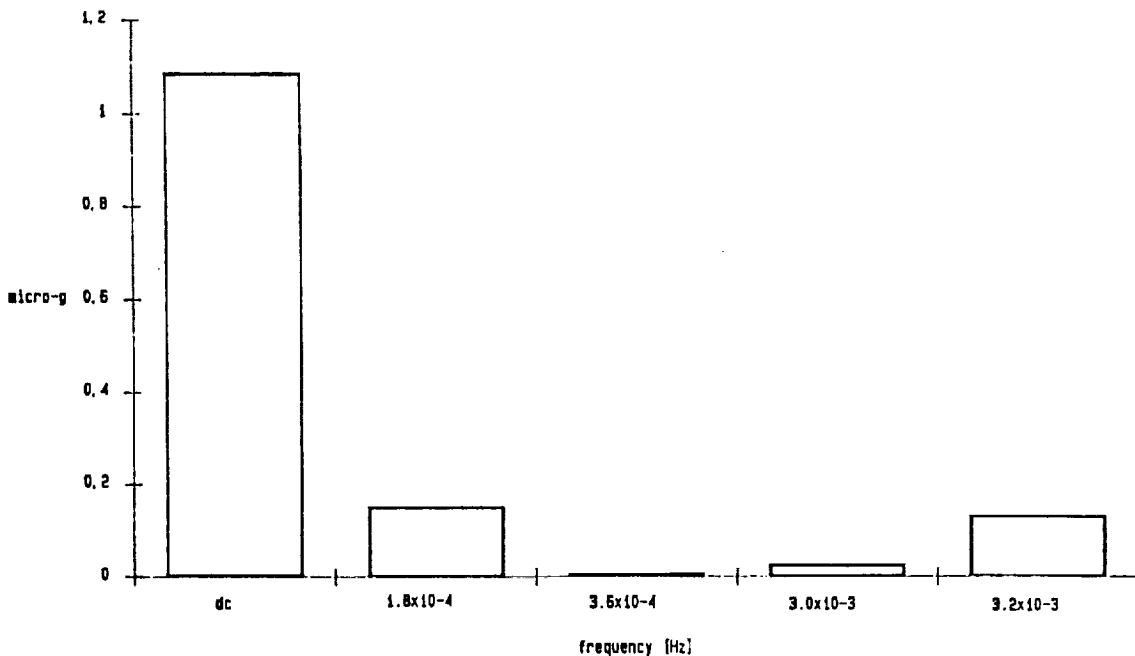


Fig. 3.2 - Residual acceleration modulus dependance on frequency for the lowest g-level: foreseen micro-g environment.

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APPENDIX B
SMITHSONIAN ASTROPHYSICAL OBSERVATORY
PROGRESS REPORT # 5

**Analytical Investigation of
Tethered Gravity Laboratory**

Aeritalia Contract 8864153

Progress Report #5

For the period 16 February 1989 through 15 May 1989

Principal Investigator

Dr. Enrico C. Lorenzini

Co-Investigators

**Dr. Mario Cosmo
Mr. David A. Arnold**

June 1989

**Prepared for
Aeritalia, Società Aerospaziale Italiana
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<p>The Smithsonian Astrophysical Observatory is a member of the Harvard-Smithsonian Center for Astrophysics</p>
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Summary

The Activity during this reporting period focused on:

- a) Fast Crawling Maneuvers (FCM) have been investigated. Specifically crawling maneuvers with time constants shorter than those used in previous analysis when librational/lateral dampers are activated.
- b) The analysis of the main perturbations acting on board VGL has been started. A Fourier analysis of the acceleration components on board the Elevator has been carried out
- c) The effect of perturbations, transmitted through the tethers by the Station, upon the acceleration level on board the Elevator has been analyzed analytically.

Figure Captions

- Figures 1(a)-1(h) Dynamic response of the VGL for a Fast Crawling Maneuver (FCM) from 167 m to 268 m off the Station with in-plane libration and lateral dampers activated ($K_\theta = K_\epsilon = 1.$)
- Figures 2(a)-2(h) Dynamic response of the VGL for a FCM from 167 m to 268 m off the Station with inplane libration and lateral dampers activated ($K_\theta = K_\epsilon = 2.$)
- Figures 3(a)-3(h) Dynamic response of the VGL for a FCM from 1404 m to 2667 m off the Station with in-plane libration and lateral dampers activated ($K_\theta = K_\epsilon = 1.$)
- Figures 4(a)-4(d) Spectra of the acceleration components (front and longitudinal) for a station-keeping phase ($l_2 = 2667$ m) with and without the action of the libration/lateral dampers.
- Figures 5(a)-5(c) Magnitude of Frequency Response Function (FRF) at the elevator for longitudinal perturbations originated at the tether/station attachment point. No tether material damping. No longitudinal dampers.
- Figures 6(a)-6(c) Magnitude of Frequency Response Function (FRF) at the elevator for longitudinal perturbations originated at the tether/station attachment point. 2% viscous tether material damping for first longitudinal mode. No longitudinal dampers.

1.0 INTRODUCTION

This is Progress Report #5 submitted by the Smithsonian Astrophysical Observatory (SAO) under Aeritalia contract 8864153, "Analytical Investigation of Tethered Gravity Laboratory," Dr. Enrico C. Lorenzini, Principal Investigator. This report covers the period from 16 February 1989 through 15 May 1989.

2.0 TECHNICAL ACTIVITY DURING REPORTING PERIOD AND PROGRAM STATUS

2.1 Fast Crawling Maneuvers (FCM)

2.1.1 Introductory Remarks

Maneuvers with time constants shorter than those used in the previous reports have been analyzed.

Even though shortening the crawling times is surely cost effective there are concerns from the dynamical point of view, namely:

- 1) Strong perturbations can be excited and are difficult to abate or have long relaxation times that defeat the goal of having the Elevator readily available at the end of the crawling. In other words, the time saved in transferring the Elevator is lost in damping the transient phases.
- 2) A libration/lateral damper must be adopted, but depending on the reel characteristics, severe constraints can be posed on its design such as high control velocities.

To this end the maximum crawling velocity of the Elevator is assumed to be equal to 1 m/sec. Furthermore the travelled distances of possible FCM have been restricted between hundreds of meters and a few Kilometers because in the low-g range the system is very sensitive to distances of a few meters. As shown in table 1 the

acceleration level varies from 0 g to 10^{-5} g over approximately 26 meters, so that a very fine g-tuning is required and this might not be achievable. On the other end, it was shown that the time constant for transfer maneuvers of several kilometers was limited by the maximum velocity of the Elevator and therefore the "Long Range" maneuver shown in Progress Report #4 can be already considered a FCM.

Table 1. Gravity Levels On-Board VGL vs. the VGL-SS Distance

a VGL(g)	L ₂ (m)
0.	141.
10^{-6}	143.8
5×10^{-6}	154.
10^{-5}	167.
5×10^{-5}	268.
10^{-4}	394.
5×10^{-4}	1404
10^{-3}	2667.
4×10^{-3}	10242.

Hence the feasibility analysis for FCM's is relevant to maneuvers from 10^{-6} g upwards.

2.1.2 Dynamic Response

For sake of brevity only two FCM's are presented in this section, namely:

a) from 167 m off the Space Station to 268 m

b) from 1404 m off the Space Station to 2667 m.

Transfer maneuvers, not shown here, have a behavior similar to the FCM's (a) and (b). The libration/lateral dampers are activated

throughout the whole simulation. In principle, these dampers could be switched off after the transient phase has been abated since the environmental forces are unable by themselves to significantly perturb the system. On the contrary the longitudinal dampers must be always activated when microgravity activities are conducted.

The librational/lateral dampers' algorithm controls the tethers' lengths according to the formulae:

$$l_{c1} = l_{o1}(1 - k_{\theta}\theta - k_{\epsilon}\epsilon/l_{o1})$$

$$l_{c2} = l_{o1}(1 - k_{\theta}\theta + k_{\epsilon}\epsilon/l_{o2})$$

The choice of the gains k_{θ} and k_{ϵ} is dictated by the necessity of abating the transient very quickly without overloading the performance of the tethers' reels.

The time constant α for FCM (a) has been reduced from the value adopted in Progress Report #3 of $1/500 \text{ sec}^{-1}$ to $1/250 \text{ sec}^{-1}$. The transferring time has been reduced from 35 min to 18 min. The maximum crawling velocity is 0.15 m/sec. The maneuver starts at 1000 sec. Two simulations are presented in this report for FCM (a). The initial conditions are the same of the corresponding simulation in Progress Report #3. The control gains in the first simulation are:

$$\text{FCM (a')} \quad K_{\theta} = K_{\epsilon} = 1$$

and in the second simulation

$$\text{FCM (a'')} \quad K_{\theta} = K_{\epsilon} = 2$$

Figures 1(a)-1(h) show the dynamic response of simulation FCM (a'). The travelled length [Figure 1(a)] does not show great differences from the corresponding run presented in Progress Report #3, the final length, however, is reached in a shorter time. Figures 1(b) and 1(c) show the terms $k_{\theta}\theta$ and $k_{\epsilon}\epsilon$ respectively. The librational term has a peak of approximately 0.25% of the tether

length. The behavior is essentially smooth except for the initial phase that is related to the initial conditions. A typical crawling should be started only when all transient phases are abated in order not to worsen the perturbations excited by the maneuver itself. Moreover such transient phases should be damped out with a control algorithm with gains' value which increase with time in order to avoid discontinuities. The lateral damping term on the other hand, has the typical behavior of underdamped systems. From the plot [Figure 1(c)] it results that the tether deployers must be able to reel in and out a peak length (time ~ 2000 sec) of approximately 2.5 m in approximately 5 minutes which corresponds to a reel velocity of about 8×10^{-3} m/s, which is well within the capability of current tethers' reels.

Figures 1(d) and 1(e) show the two libration angles θ and ϕ and the in-plane lateral oscillation respectively. Notice that they follow the behavior of the two damping terms. The tether tensions are shown in Figure 1(f). The two peaks in the upper tension are due to the acceleration and deceleration phase of the crawling maneuver. The overshoot however does not exceed the 2% of the equilibrium value.

Figure 1(g) shows the front and lateral component of the acceleration acting on board the VGL. The front component has a peak of 4.8×10^{-5} g which is 4% less than the final steady-state acceleration of 5×10^{-5} g. However, the transient phase is quite long, the logarithm decrement is equal to 0.6 and the corresponding damping ratio is equal to 10%. Figure 1(h) shows the longitudinal component of the acceleration acting on board the VGL. The peak value of 1.5×10^{-4} g (Acceleration phase), is three times bigger than the final steady-state value. The transient phase for the longitudinal component is somewhat shorter than the front component.

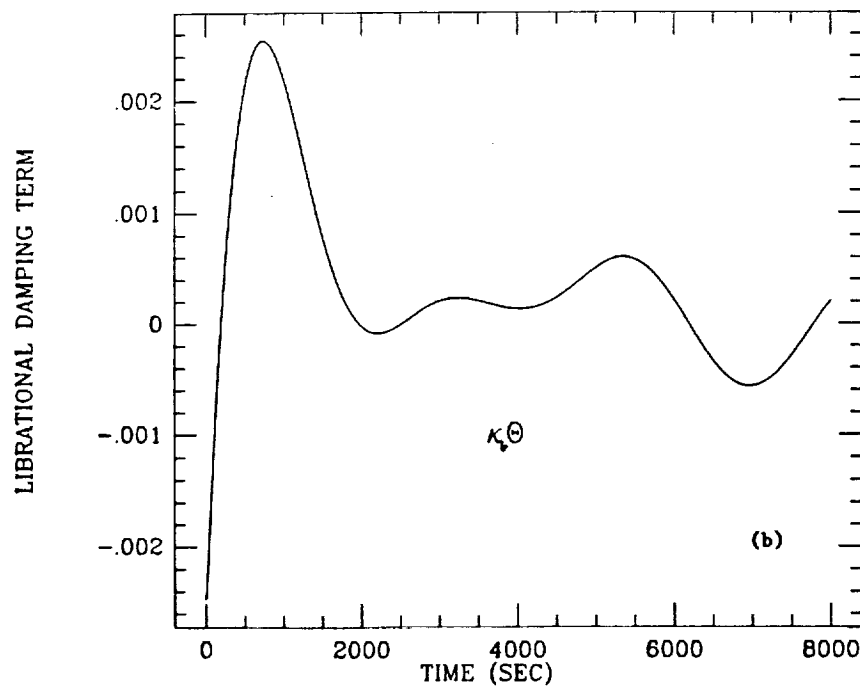
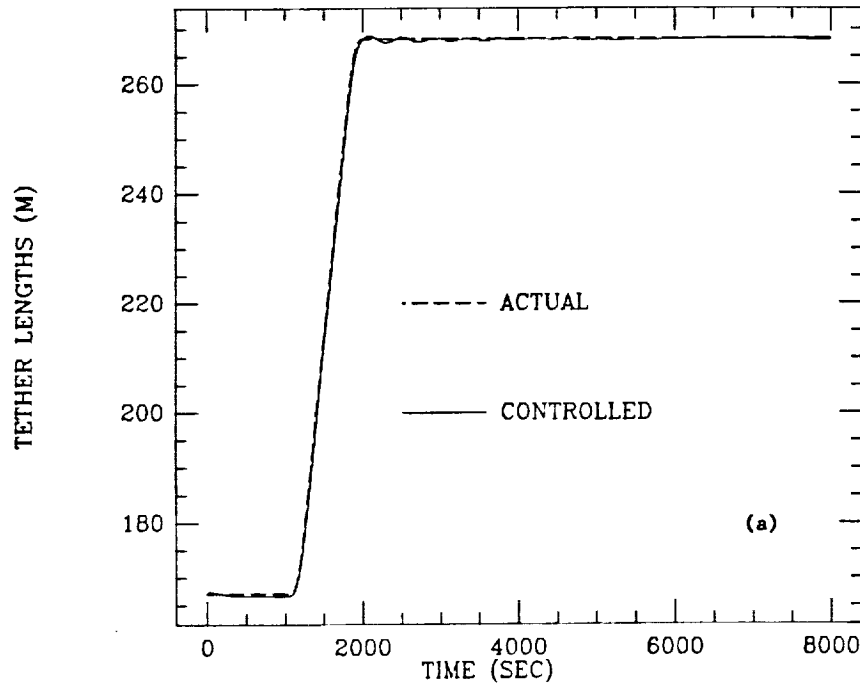
In order to increase the damping action the control gains have been increased in simulation FCM (a"). Figures 2(a)-2(h) show the dynamic response for this case. This set of figures must be compared with the corresponding plots of Figure 1. Obviously the travelled length, the libration angles θ and ϕ , and the VGL lateral deflection did not change. The two damping terms k_θ and k_ϕ

increased linearly with the control gain [Figure 2(b) and 2(c)]. The tether tension [Figure 2(f)] is almost the same of the previous run, actually the peak is slightly reduced. The transient of the front component of the acceleration [Figure 2(g)] is shorter compared to the corresponding plot [Figure 1(g)]. The logarithmic decrement is 1.3 corresponding to a damping ratio of 20% showing a linear dependence, with the control gains k_θ and k_ϵ . The same applies to the longitudinal component of the acceleration acting on board the VGL.

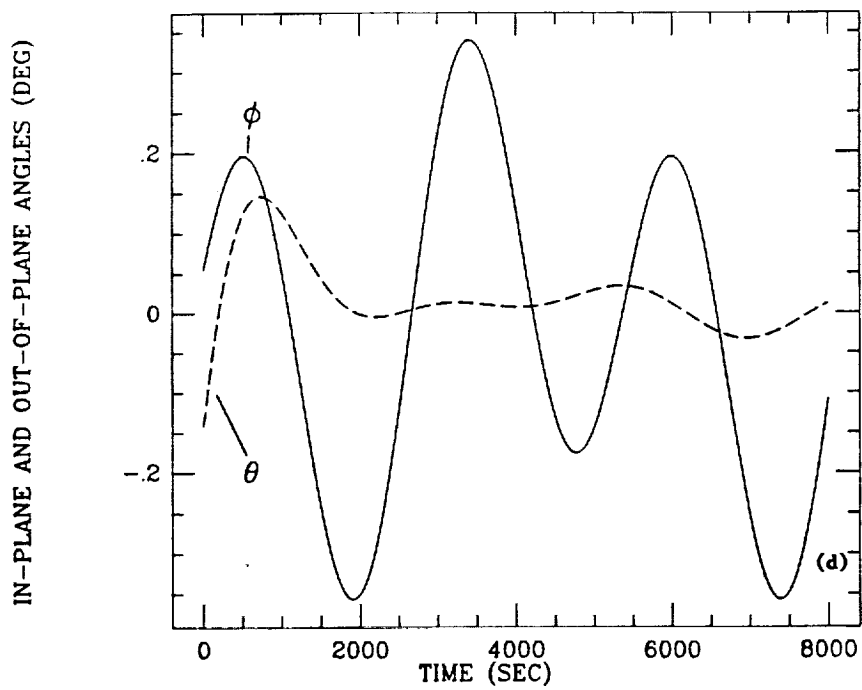
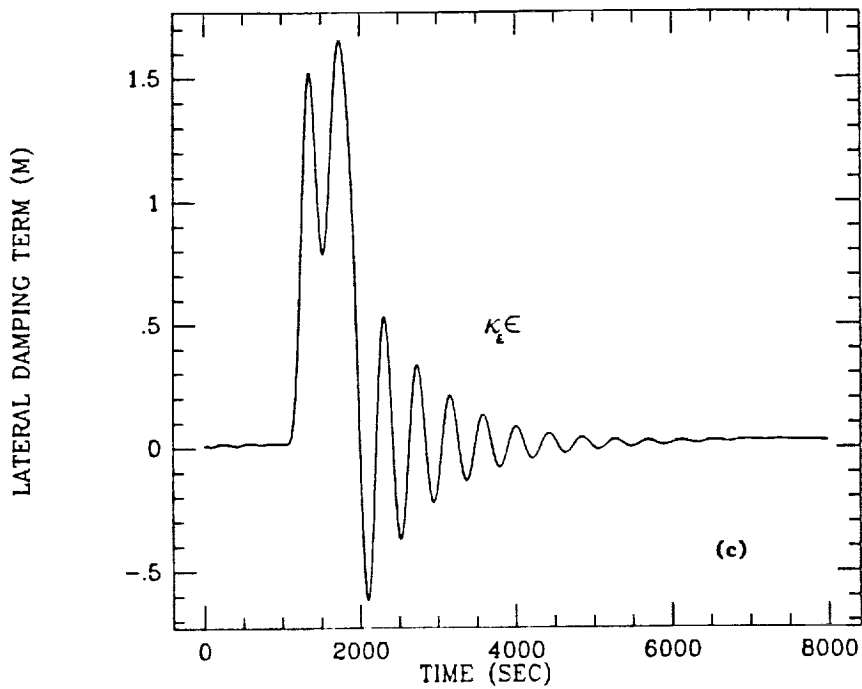
Figures 3(a)-3(h) show the dynamic response of simulation FCM (b). For the reasons mentioned above, the initial phase is meaningless because the initial conditions are taken from the corresponding simulation presented in Progress Report #4. In this case the crawling starts at 5000 sec so that the initial dynamic "noise" is completely abated. The time constant α has been reduced from the value adopted in Progress Report #3 of $1/1000 \text{ sec}^{-1}$ to $1/500 \text{ sec}^{-1}$. The transfer time is reduced from 70 min to 35 min. The maximum crawling velocity is 0.9 m/sec. The control gains adopted are:

$$K_\theta = K_\epsilon = 1$$

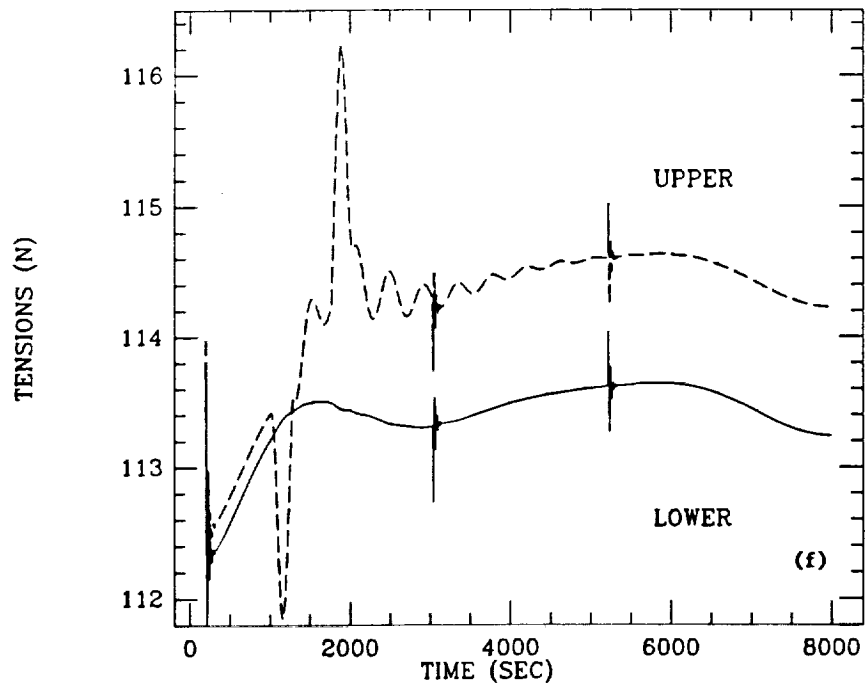
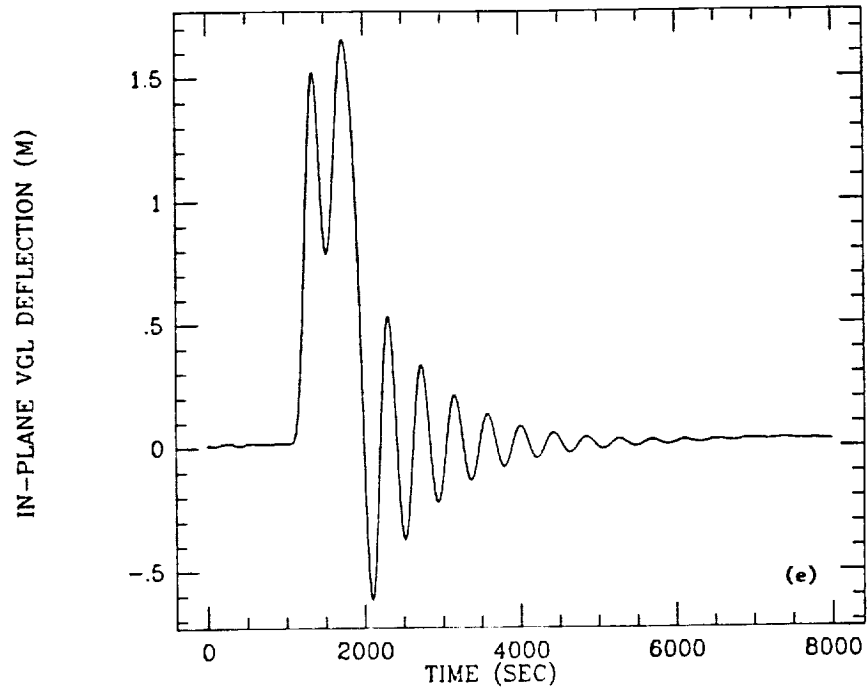
Figure 3(a) shows the tether length while, Figures 3(b) and 3(c) show the damping terms $k_\theta \theta$ and $k_\epsilon \epsilon$, respectively. Also in this case the reel performance is well within the current capabilities of tethers' reels. The maximum velocity of 0.2 m/sec takes place at approximately 7500 sec and it is related to the lateral damping term. The two libration angles θ and ϕ , shown in Figure 3(d), and the lateral deflection of the VGL, shown in Figure 3(i), do not show any particular feature. The same applies to the tethers' tensions [Figure 3(f)]. Figure 3(g) shows the front and lateral component of the acceleration acting on board the VGL. The front component has a peak of $2.8 \times 10^{-4} \text{ g}$. The transient is quite short, the logarithmic decrement is equal to 1.1 and the corresponding damping ratio is equal to 17%. The longitudinal component is shown in Figure 3(h). The peak is about 20% larger than the final steady state value of 10^{-3} g . The longitudinal component has the same damping characteristics of the front component. Since simulation FCM (b) shows satisfactory results we deemed unnecessary to run other simulations with higher gains.



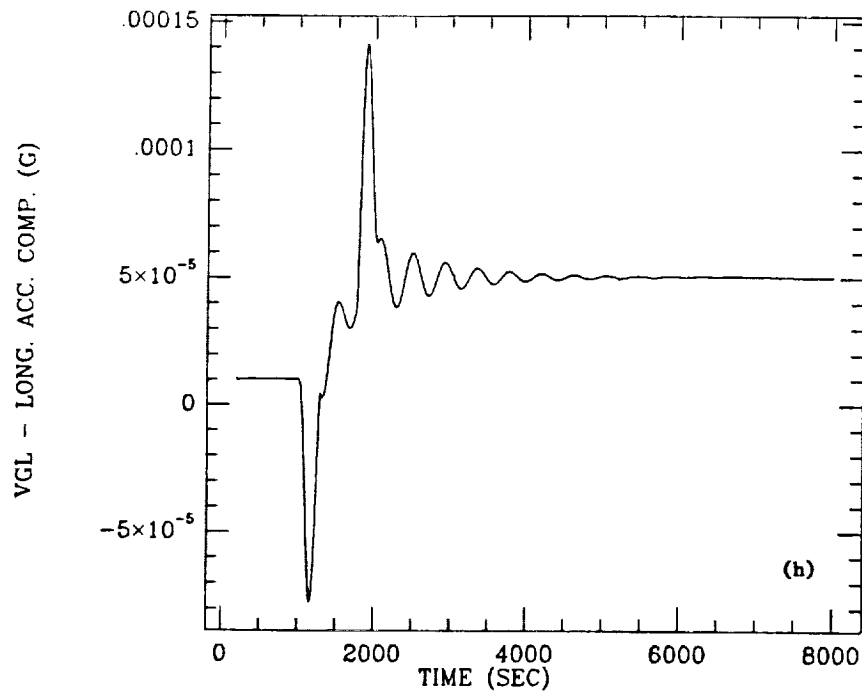
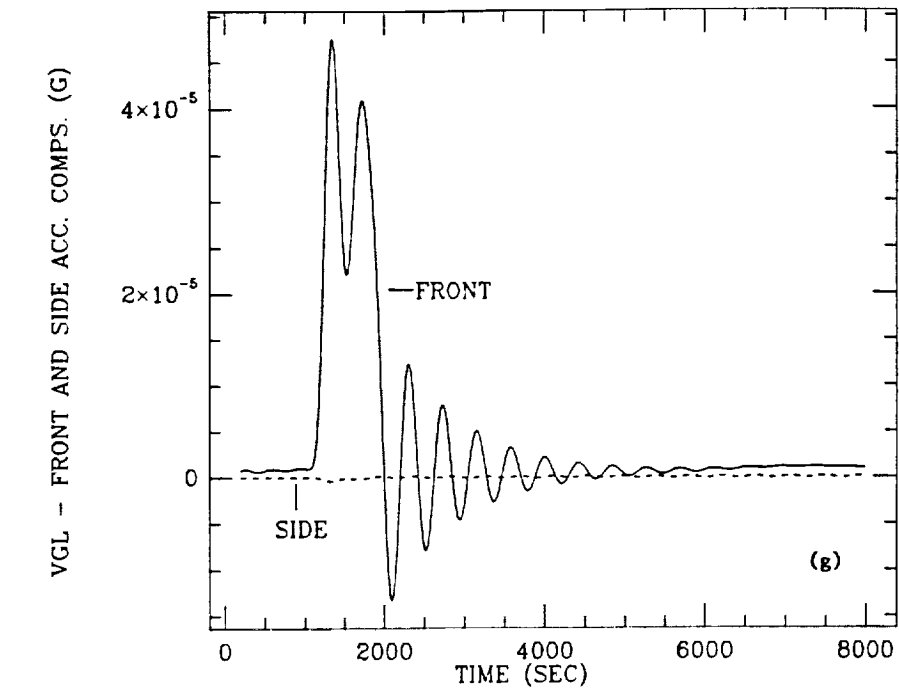
Figures 1(a)-1(b)



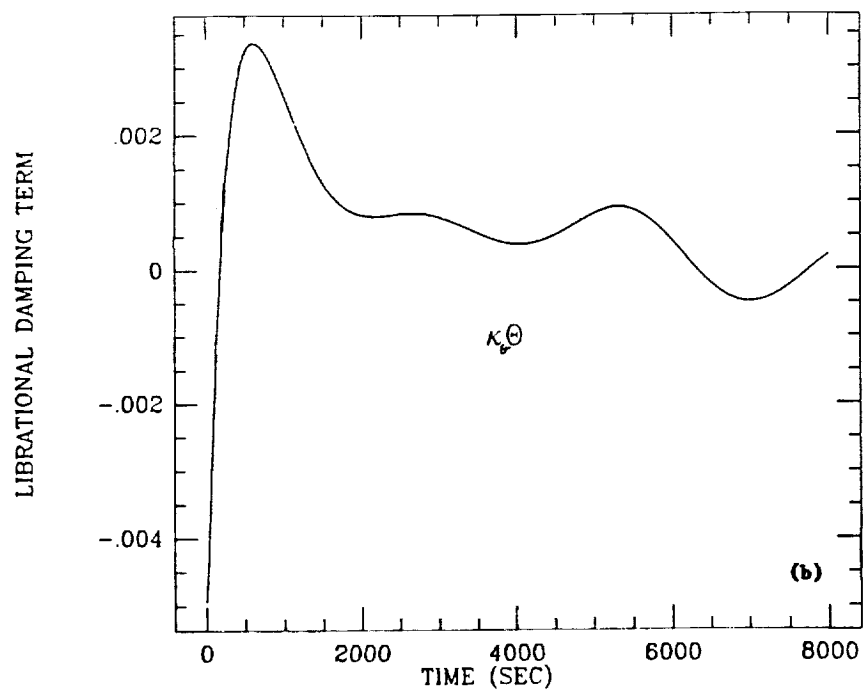
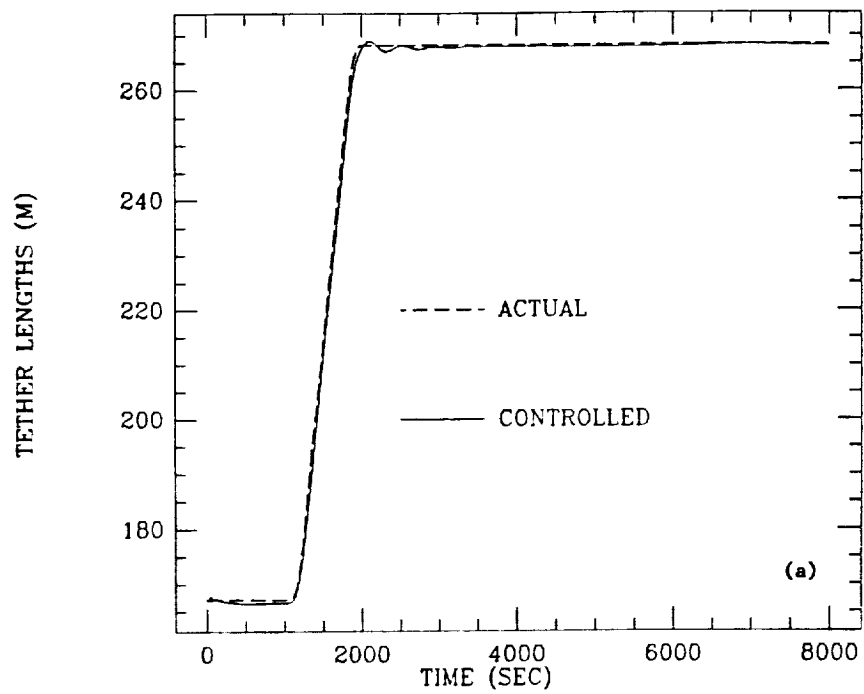
Figures 1(c)-1(d)



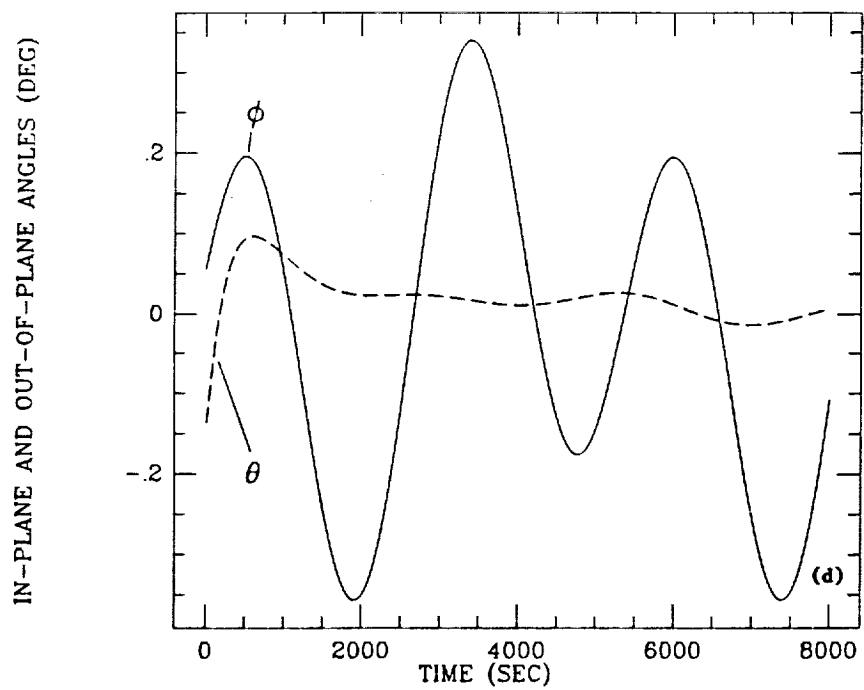
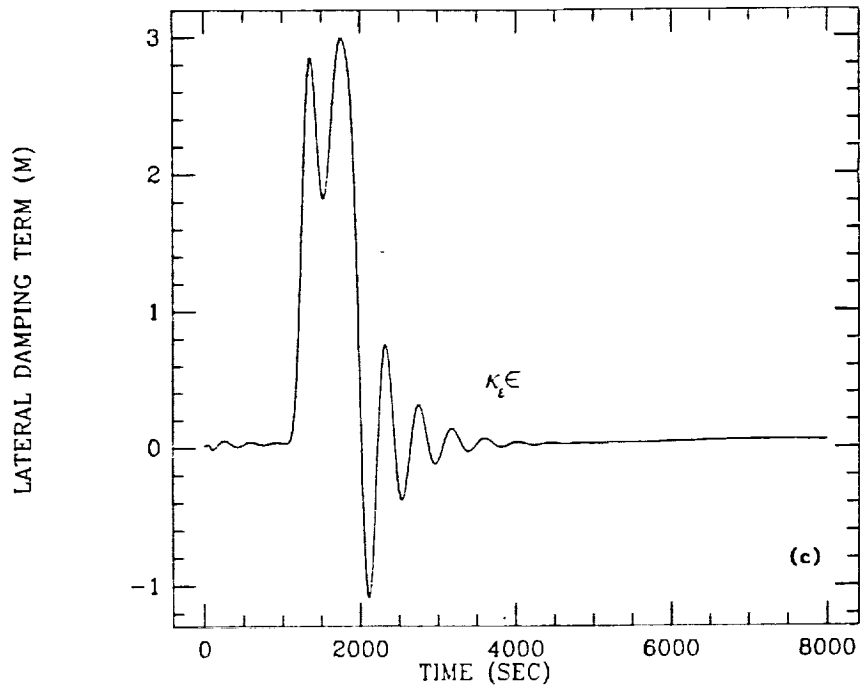
Figures 1(e)-1(f)



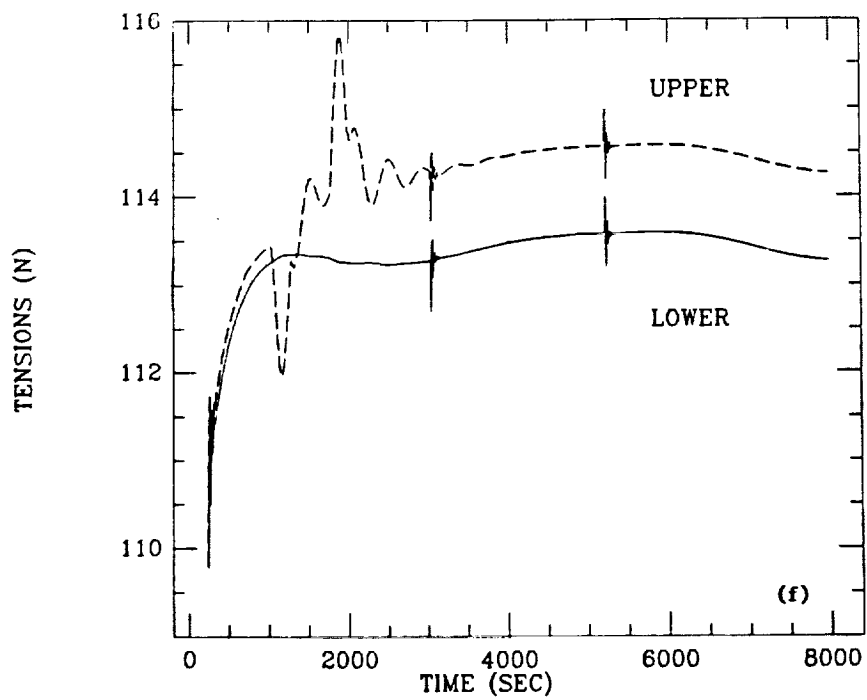
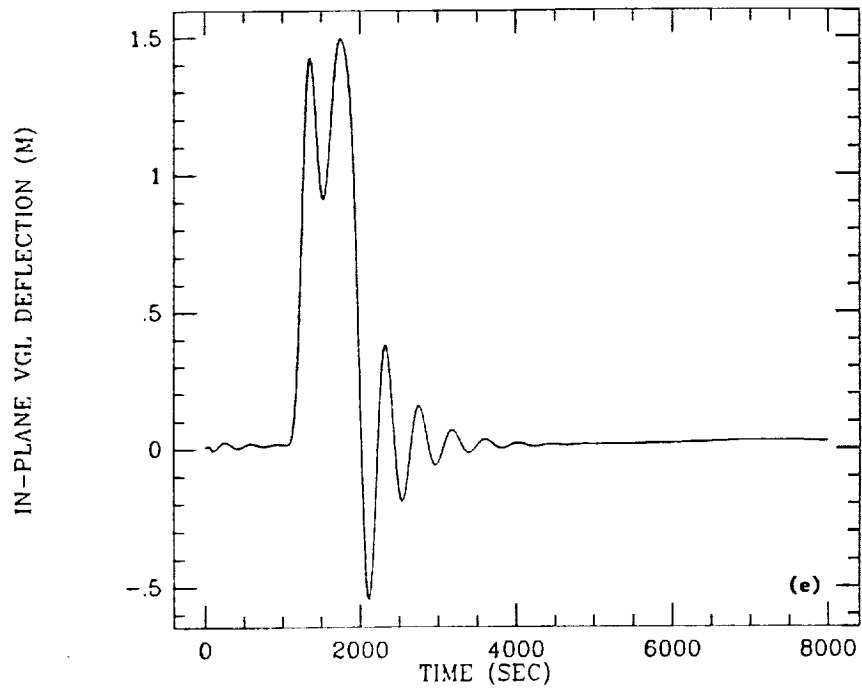
Figures 1(g)-1(h)



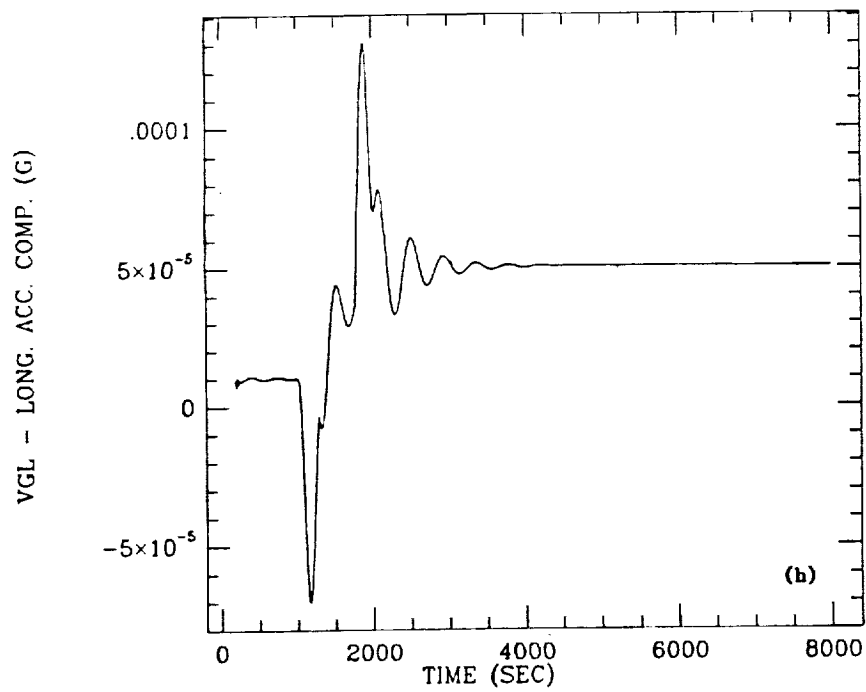
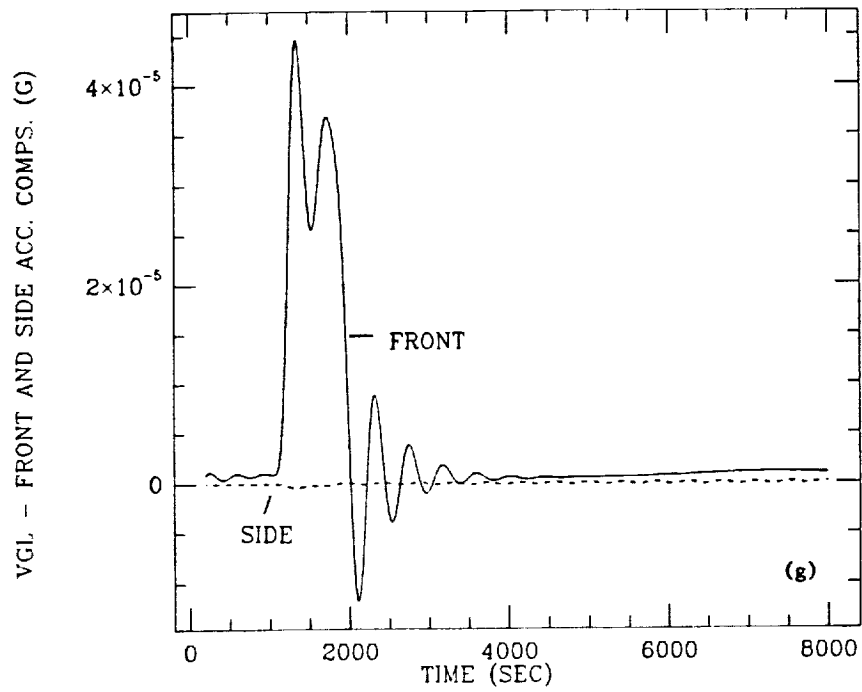
Figures 2(a)-2(b)



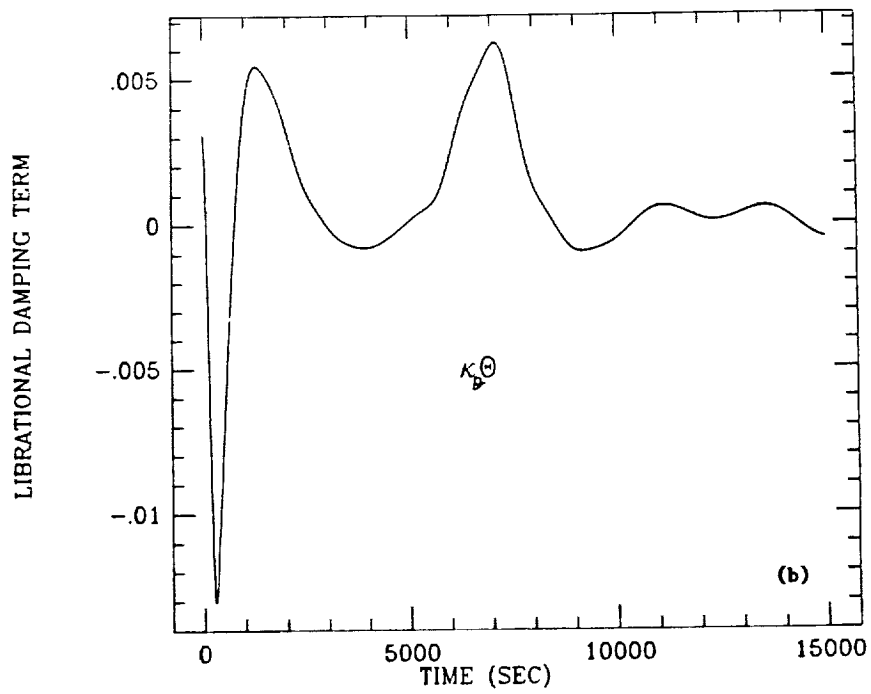
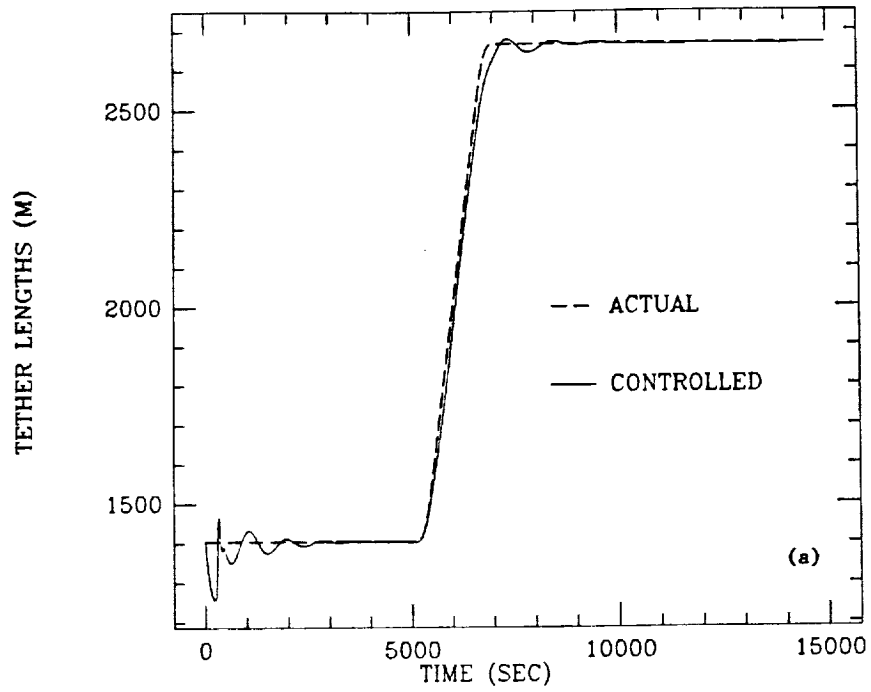
Figures 2(c)-2(d)



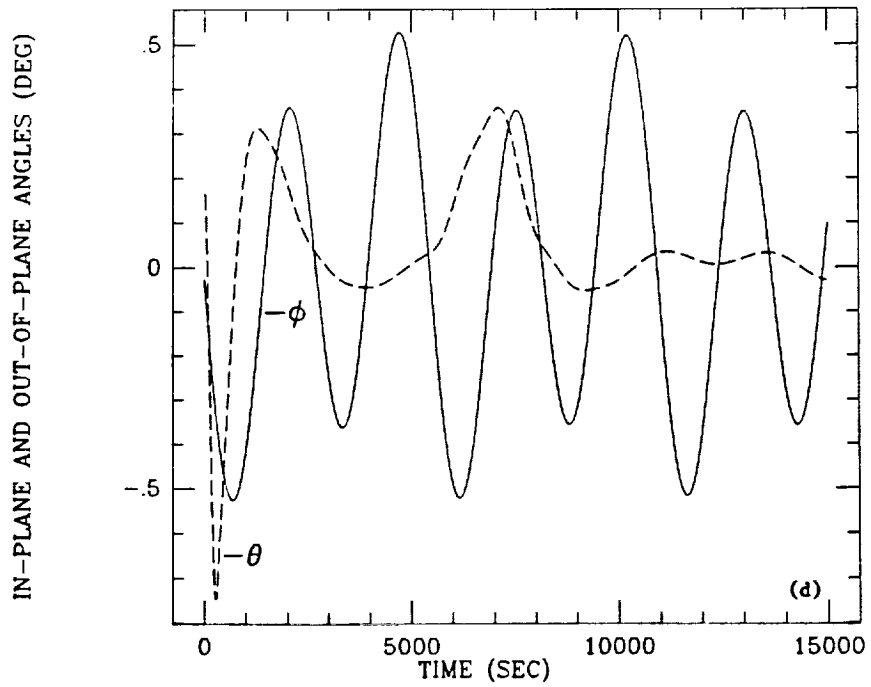
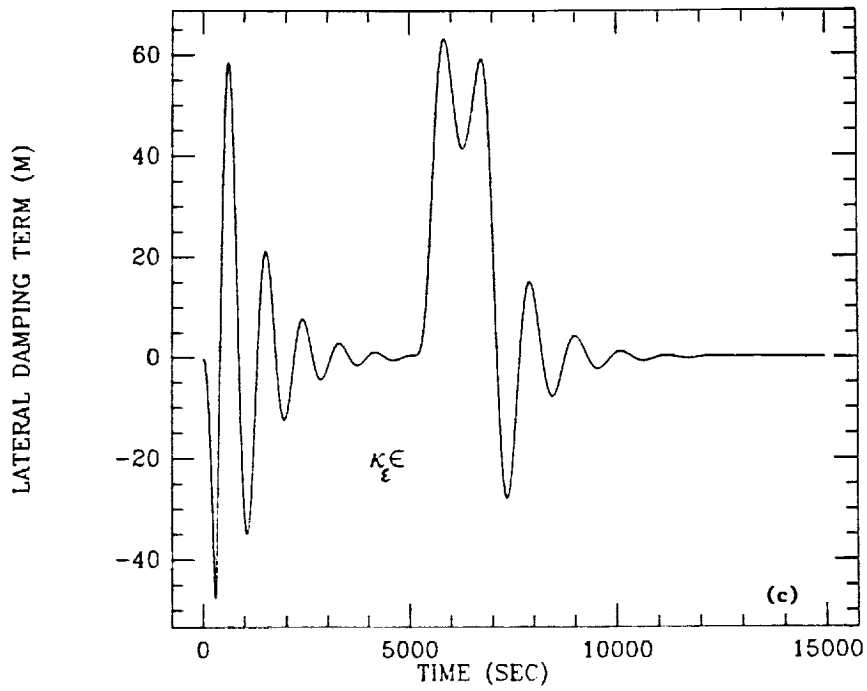
Figures 2(e)-2(f)



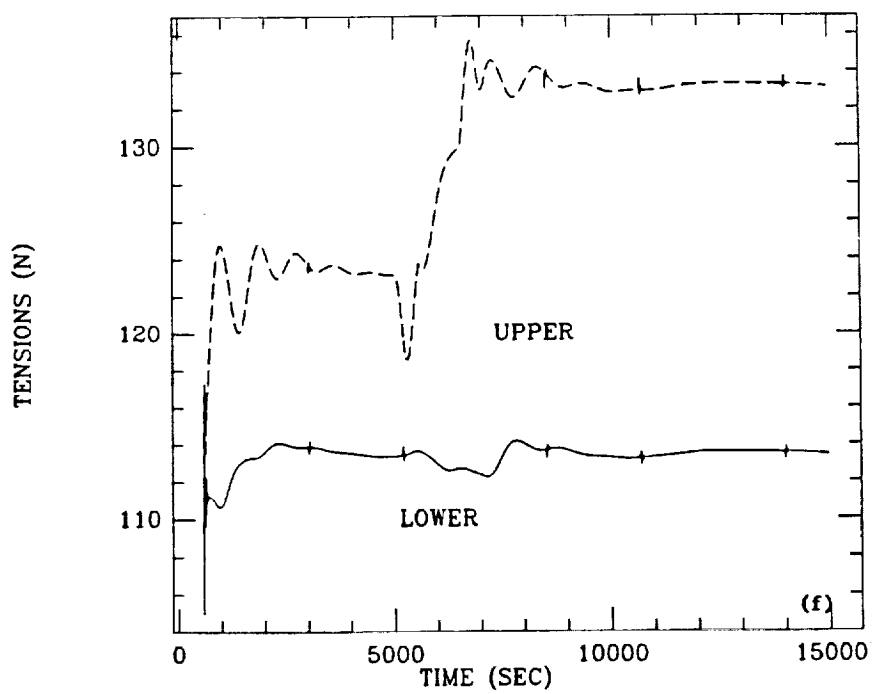
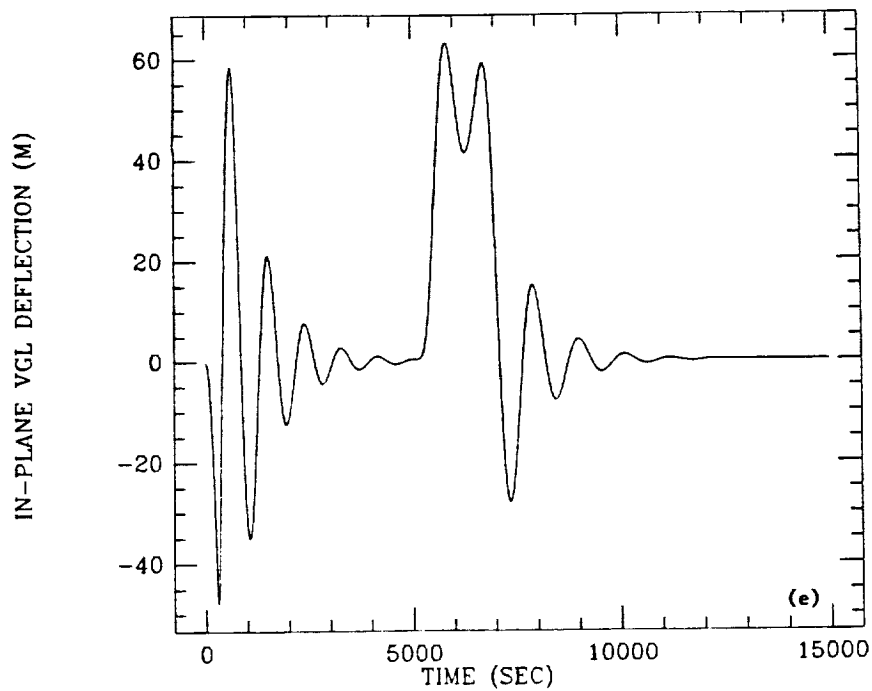
Figures 2(g)-2(h)



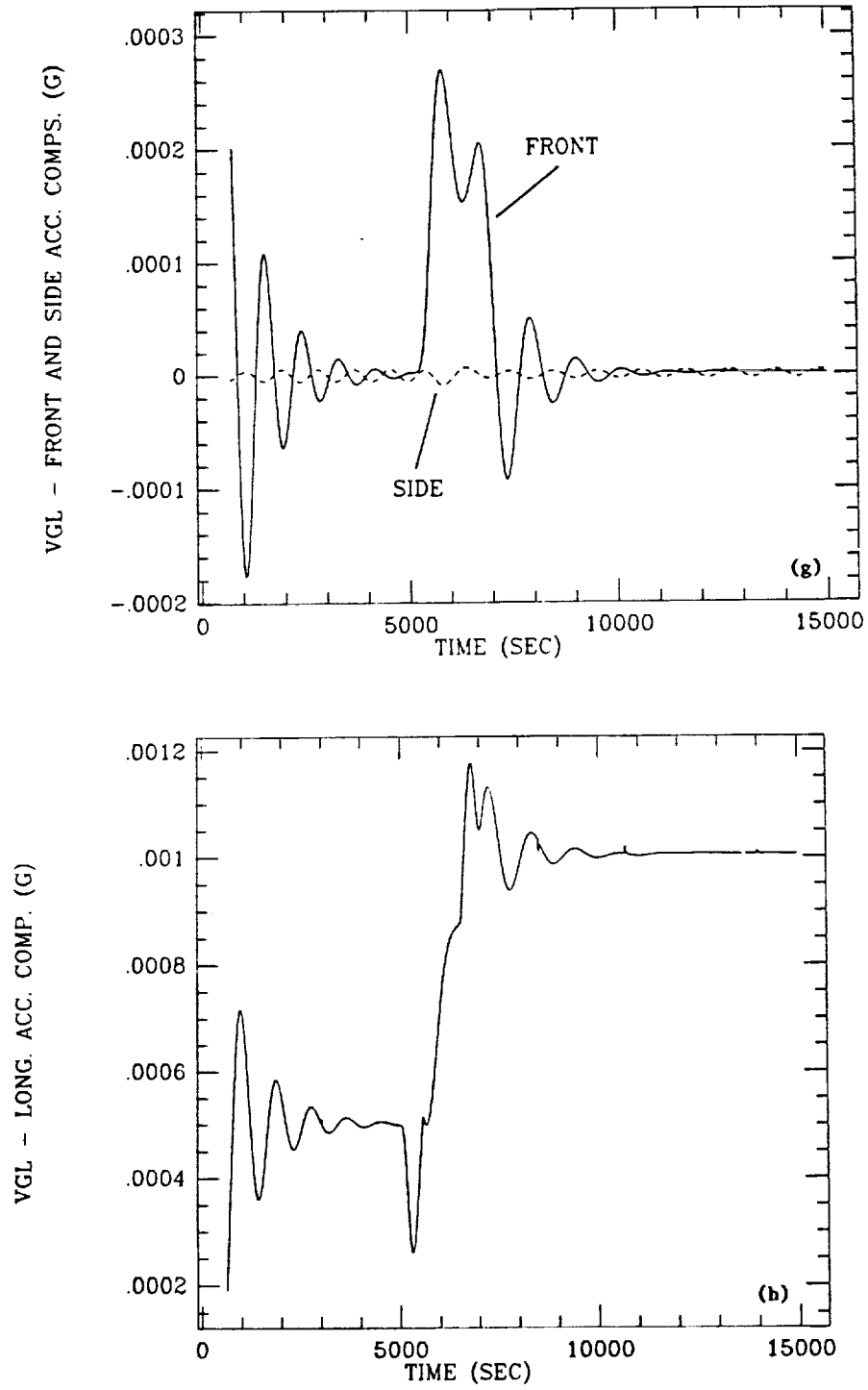
Figures 3(a)-3(b)



Figures 3(c)-3(d)



Figures 3(e)-3(f)



Figures 3(g)-3(h)

2.2 Accelerations On Board VGL

The study performed so far has shown the effects of some of the main environmental perturbations upon the VGL acceleration's levels. Nevertheless it seems necessary at this point to focus the attention on the general perturbations that affect the "quality" of the g-levels on board the VGL. Schematically these perturbations can be divided in four main categories:

- 1) Orbital perturbations (J_2 , atmospheric drag, attitude motions)
- 2) Tether-related perturbations (librations, longitudinal oscillations, lateral oscillations)
- 3) VGL-perturbations (structural, man-made, outgassing)
- 4) Space Station perturbations (all disturbances coming from the station and transmitting through the tether)

These categories are not actually independent from each other and some phenomena can fit one or another. In all the simulations presented in our studies the VGL is acted upon by J_2 and atmospheric drag. MASTER20 code is equipped also with rigid body dynamics and, under Aeritalia directions, some simulations with rotational dynamics will be performed. The tethers' inertia contribution has not been taken into account in the crawling simulations except for the station-keeping phases. Nevertheless the simplified modelization is able to represent the most important features of VGL dynamics. Perturbations related to VGL structural or attitude control systems can not yet been modelled until a preliminary design of the VGL itself will be available at the end of this study. The Space Station can be a source of non negligible noise because of its flexibility and the activities envisioned on board the station.

The following analysis starts dealing with some of the above mentioned topics, namely the noise related to the orbital dynamics, to the tether flexibility and to the Space Station.

2.2.1. Spectral Analysis of the Accelerations Acting On Board VGL

An harmonic analysis of the accelerations acting on board VGL was performed. Even though Fourier analysis is useful in finding the frequencies at which the perturbations act, care must be taken in analyzing the spectral magnitudes. These, in fact, are strictly related to the initial conditions and above all to the damping acting on a particular mode. Hence the spectral analysis should be used primarily to identify the frequency content of a given signal.

To this end the station-keeping phase of FCM (b), when $l_2=2667$ m, has been compared to the same phase of the simulation presented in Progress Report #4 (Figures 5). The main difference being that in FCM (b) the libration/lateral dampers are activated while in the other simulation the lateral mode is strongly excited. Both systems are modelled by three lumps so that the vibration modes of the tethers can not be seen.

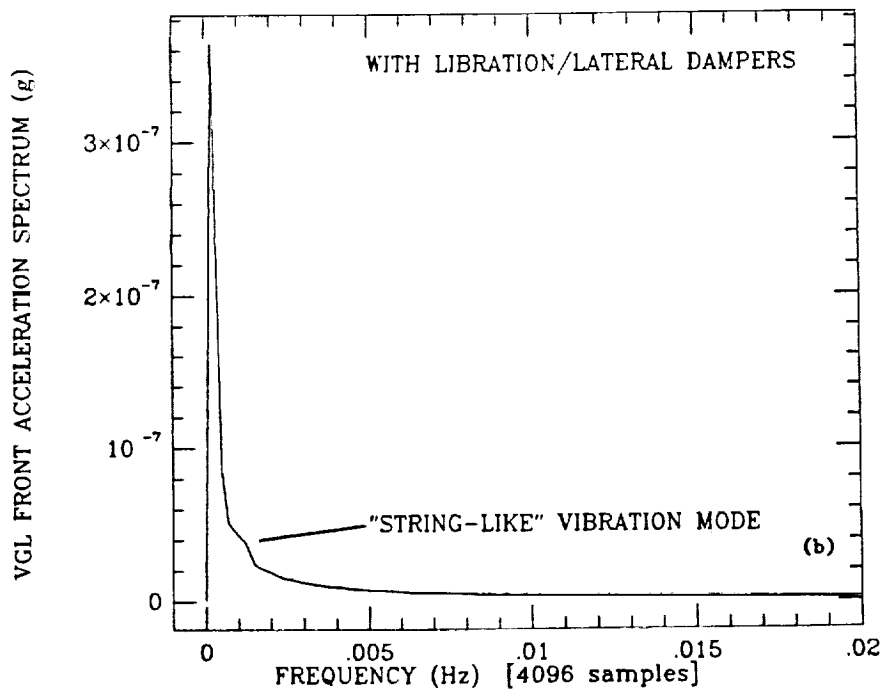
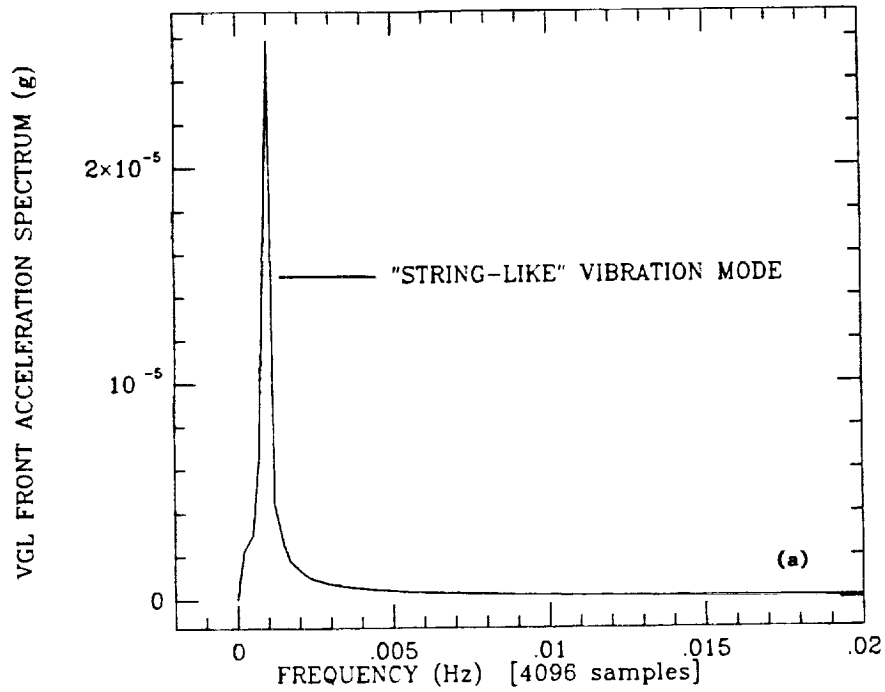
In Progress Report #4 the natural frequencies of the equivalent 2-mass/2-spring system are as follows

3.12×10^{-2} Hz	I "Spring-mass" mode
1.15×10^{-1} Hz	II "Spring-mass" mode
9.12×10^{-4} Hz	Lateral vibration mode

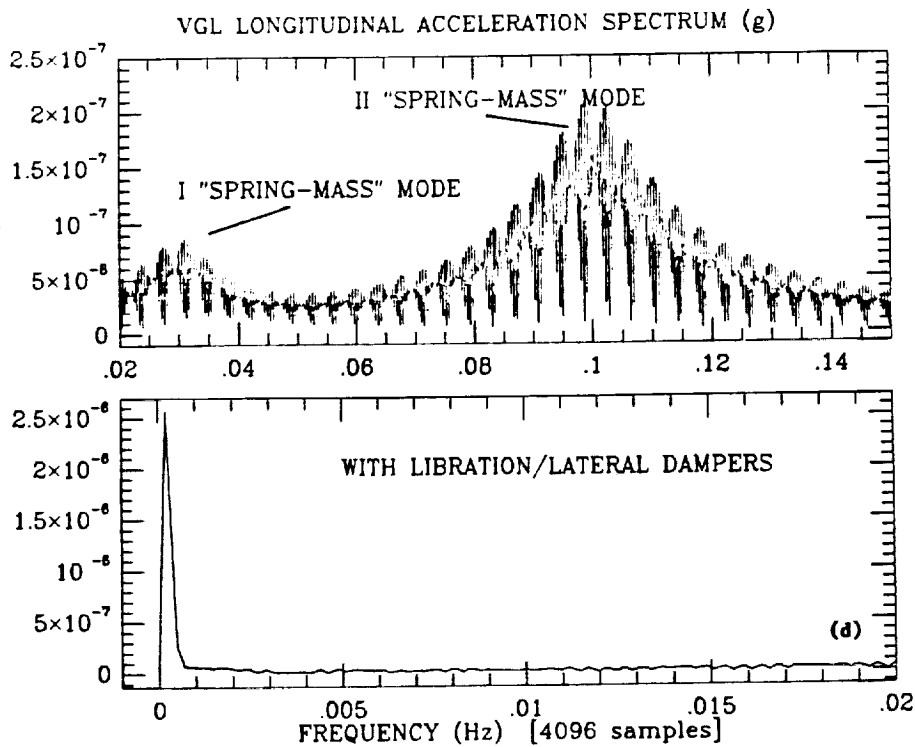
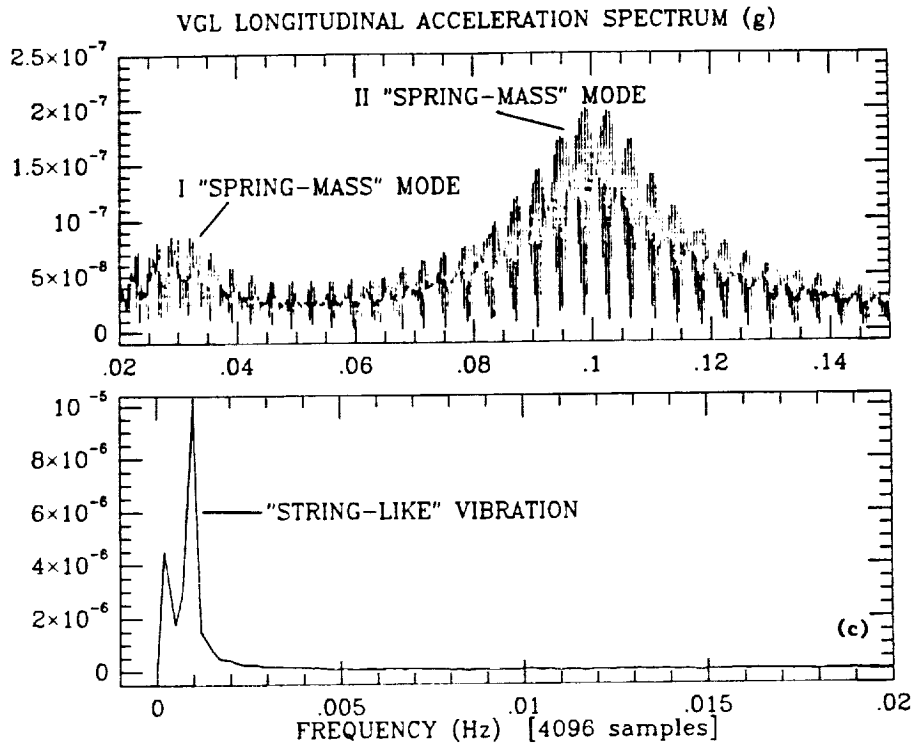
Figures 4(a)-4(d) show the spectra of the front and longitudinal component of the acceleration acting on board the VGL. The action of the libration/lateral dampers is quite evident when the spectra of the front components are compared [Figure 4(a) and 4(b)]. The effects of the accelerations due to the lateral oscillations are the most significant. The amplitude of the lateral mode has been reduced by three orders of magnitude by the damper. No peaks are present for frequencies larger than 5×10^{-3} Hz because the tether oscillatory modes are not modelled.

The longitudinal components show in both cases [Figure 4(c) and 4(d)] two separate groups of frequencies. The lower frequency ($<5 \times 10^{-3}$ Hz) is related to the orbital dynamics (first peak) and lateral oscillations (second peak), while the frequency group between 2×10^{-2} and 1.2×10^{-1} Hz is related to the tether

longitudinal dynamics. No other peaks are present for frequencies larger than 1.4×10^{-1} Hz because the tether oscillatory modes are not modelled in this simulation run. Notice that the peaks at higher frequencies present some "leakage" phenomena. This phenomena could be reduced by "Hanning" the data, which would cause however, a reduction of the harmonic amplitudes. Also for the longitudinal oscillations the effect of the libration/lateral dampers is evident.



Figures 4(a)-4(b)



Figures 4(c)-4(d)

2.2.2. Disturbance Propagation in Variable Gravity Laboratory System

Oscillations of the tether attachment point to the station generate waves which propagate along the tether to the elevator and beyond to the end platform. Since the station is a source of non-negligible dynamic noise the impact of the station-related disturbances on the elevator acceleration level may be more important than the effect of the environmental perturbations. The station accounts for oscillations with a wide range of frequencies. In particular, the low frequency (around 10^{-3} Hz) disturbances are associated with aerodynamic and orbital perturbations; the medium frequency (from 10^{-2} Hz to 10 Hz) disturbances with the structural vibrations of the station; and the high frequency (> 10 Hz) disturbances with rotating machinery and human activity on board the station.

The wave propagation is affected by the tether characteristics of mass, stiffness, and material damping, by the tensions in the two tether segments, and by the geometry of the system. The impact of the longitudinal waves upon the elevator acceleration level also varies depending on the presence or absence of longitudinal dampers at the tether attachment points.

The following analysis is based on an analytical solution to the wave equations in a two-tether-segment system (like the VGL) derived in reference 1. This model is based on the assumptions of small oscillations, viscous material damping, tether as a perfectly elastic continuum, and unconstrained elevator and end platform. The equations of motion in non-dimensional form are given by [1]:

$$\begin{aligned}
 u_{jtt} &= \varepsilon_j^2 \left\{ 1 + b \frac{\partial}{\partial t} \right\} u_{jz_j z_j} + \gamma u_j & j &= 1, 2 \\
 u_{2tt} &= -\varepsilon_2^2 a_2 \lambda_2 \left\{ 1 + b \frac{\partial}{\partial t} \right\} u_{2z_2} + \gamma u_2 & z_2 &= 1 \\
 u_{1tt} &= -\varepsilon_1^2 a_1 \lambda_1 \left\{ 1 + b \frac{\partial}{\partial t} \right\} u_{1z_1} - \varepsilon_2^2 a_1 \lambda_2 \left\{ 1 + b \frac{\partial}{\partial t} \right\} u_{2z_2} + \gamma u_1 & (1) \\
 & & z_1 &= 1; z_2 = 0 \\
 u_2(0, t) &= u_1(1, t)
 \end{aligned}$$

$$u_1 = e^{i\omega t}$$

$$z_1 = 0$$

The subscripts t and z_j indicate partial derivatives with respect to time and vertical coordinates respectively. The dimensionless vertical coordinates for tether segments 1 and 2 are $z_1 = Z_1/L_1$ and $z_2 = Z_2/L_2$ where Z_1 and Z_2 are the dimensional quantities. Likewise u_1 and u_2 are the dimensionless longitudinal tether stretches while $t = \Omega W$ is the dimensionless time. μ is the tether linear density, Ω the orbital rate, m_1 and m_2 the masses of the elevator and the upper-platform respectively, EA the tether stiffness, $E'A$ the tether axial viscosity, and ω the angular frequency of the perturbation. The dimensionless coefficients in eqt. (1) are as follows: $\varepsilon_1 = c/\Omega L_1$, $\varepsilon_2 = c/\Omega L_2$, $a_1 = L\mu/m_1$, $a_2 = L\mu/m_2$, $\lambda_1 = L_1/L$, $\lambda_2 = L_2/L = 1 - \lambda_1$, $b = E'A\Omega/EA$ and $\gamma = 3$, where $c = (EA/\mu)^{1/2}$ is the longitudinal wave speed, L_1 and L_2 are the lengths of the two tether segments, while L is the overall length of the tether.

As indicated in reference 2 the tether damping is best approximated by a combination of viscous and structural damping. The purely viscous model, however, leads to an analytic solution of the equation and provides results which are accurate enough in the neighborhood of a specific frequency. Once the actual damping value is known for a certain frequency (not yet the case for long braided tethers in space) the equivalent viscous damping value for that frequency can be adopted to interpret the results. The viscous damping model provides results which are conservative for frequencies lower than the equivalent-damping-frequency and non-conservative for higher frequencies.

The longitudinal acceleration at the elevator for a unit sinusoidal longitudinal acceleration at the tether/station attachment point, that is the Frequency Response Function (FRF), is given by:

$$R_1(1) = [\cos\beta_1 - \delta_1 \sin\beta_1 - \frac{\sin\beta_1 \sin\beta_2 + \delta_2 \sin\beta_1 \cos\beta_2}{\cos\beta_2 - \delta_2 \sin\beta_2}]^{-1} \quad (2)$$

where

$$\beta = \sqrt{\frac{\omega^2 + \gamma}{1 + i\omega b}}$$

$$\beta_1 = \beta/\epsilon_1$$

$$\beta_2 = \beta/\epsilon_2 \tag{3}$$

$$\delta_1 = \beta_1/(a_1\lambda_1)$$

$$\delta_2 = \beta_2/(a_2\lambda_2)$$

Figures 5(a), 5(b), and 5(c) show the magnitude of the longitudinal wave FRF at the elevator for a fractional distance between elevator and station $\lambda_1 = 0.1, 0.5$, and 0.9 respectively. The material damping is assumed equal to zero and the plots clearly show the longitudinal resonance frequencies for the three different position of the elevator along the tether. The resonance spikes for these undamped cases are of course infinite and are limited in the plots only as a result of the sampled plotting step. In Figure 5(a) the two lowest frequencies of 0.04 Hz and 0.14 Hz are the two spring-mass longitudinal modes of the system. The other spikes correspond to the harmonics of the longitudinal modes of tether segment 2 (between the elevator and the end platform) while the spike at 1.76 Hz is the first longitudinal harmonic of tether segment 1. In Fig. 5(b) the two lowest frequencies of 0.036 Hz and 0.097 Hz are the spring-mass modes of the system. The remaining spikes are the longitudinal harmonics of tether segments 1 and 2 which are paired together. In Fig. 5(c) the two spring-mass modes have frequencies of 0.04 Hz and 0.19 Hz. The remaining spikes are the harmonics of the longitudinal modes of tether segment 1 while the spike at 1.76 Hz is the first longitudinal mode of tether segment 2.

If we now assume a 2% damping ratio for the first longitudinal tether mode, as adopted in the numerical simulation runs, the resonance spikes are attenuated and finite as shown in Figs. 6(a), 6(b), and 6(c). We must point out, however, that low frequency disturbances (< 0.2 Hz) propagate with no attenuation. The small material damping has a very limited effect on the spring-mass modes of the system. Furthermore, these modes have frequencies

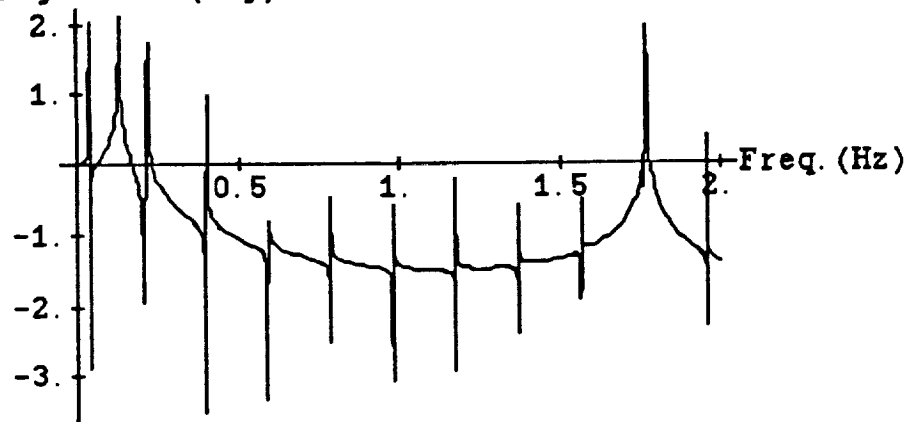
close to the first bending mode of the station which is equal to 0.1 Hz for the 3-m-truss station and to 0.2 Hz for the 5-m-truss station. The amplitudes of the spring-mass modes can be reduced by adding tuned longitudinal dampers (as already accounted for in the numerical model) which are not included in this analytical model. However, the frequencies of the spring-mass modes, around 0.1 Hz, are still far too high to provide a satisfactory attenuation of the first structural mode of the station which is also around 0.1 Hz.

The high frequencies of the spring-mass modes are a result of the tether stiffness characteristics. Stiff tethers transmit disturbances better than soft tethers. This analysis of the wave propagation emphasizes the need for a softer tether and eventually for assessing the minimum value of the tether diameter which provides the desired life expectancy.

2.2.2.1 References to Section 2.2.2

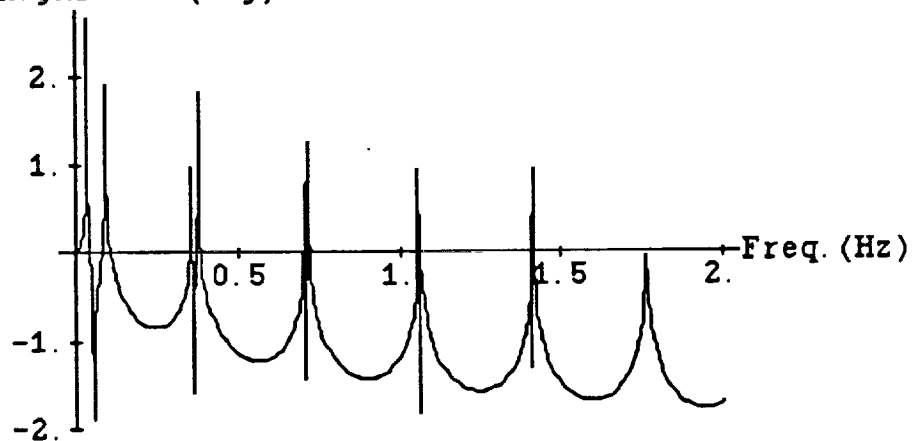
- [1] E. C. Lorenzini and M. Cosmo, "Wave Propagation in the Tether Elevator/Crawler System", to appear in Proceedings of the Tether Dynamics Workshop, 16 May 1989, San Francisco, CA.
- [2] X. He and D. Powell, "Tether Damping in Space", to appear in Journal of Guidance, Navigation and Control, 1989.

EL,FRF Magnitude (Log)



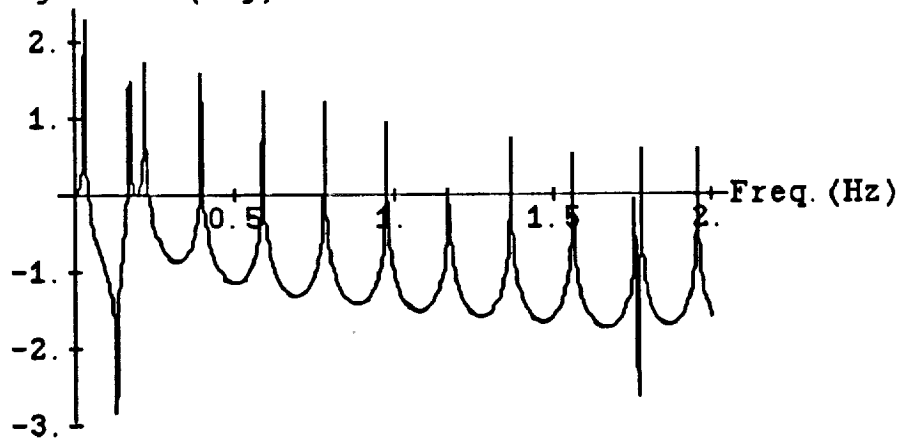
$\lambda_1 = 0.1$ (a)

EL,FRF Magnitude (Log)



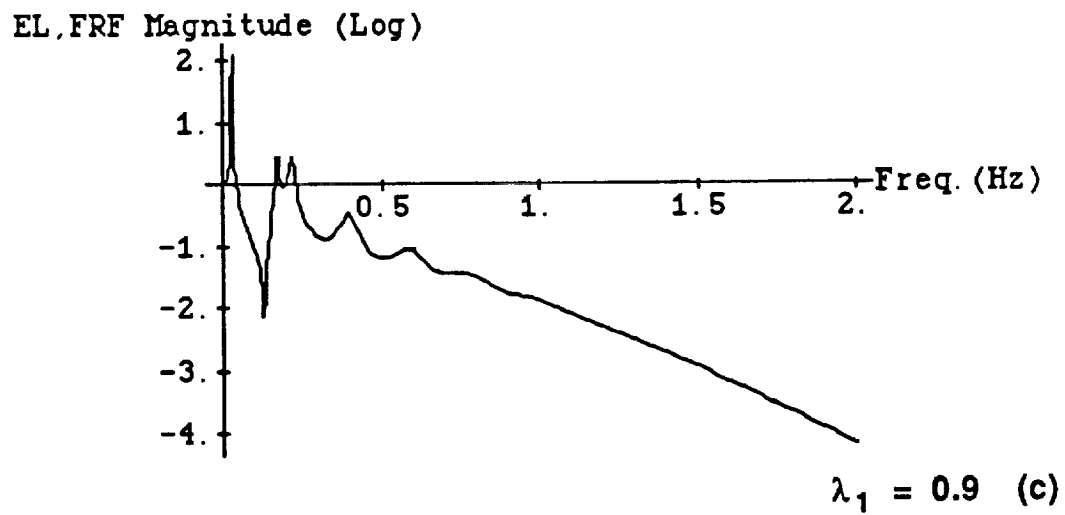
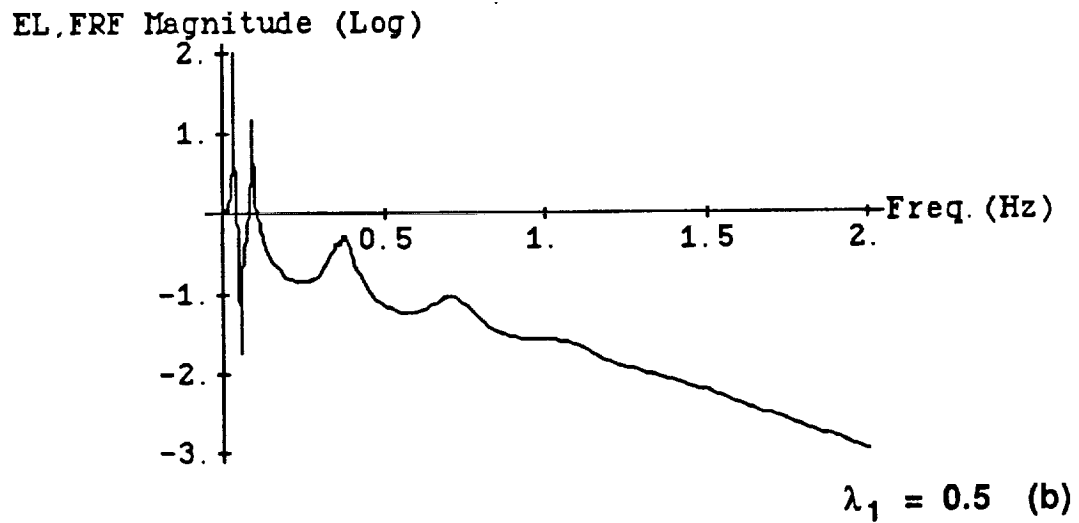
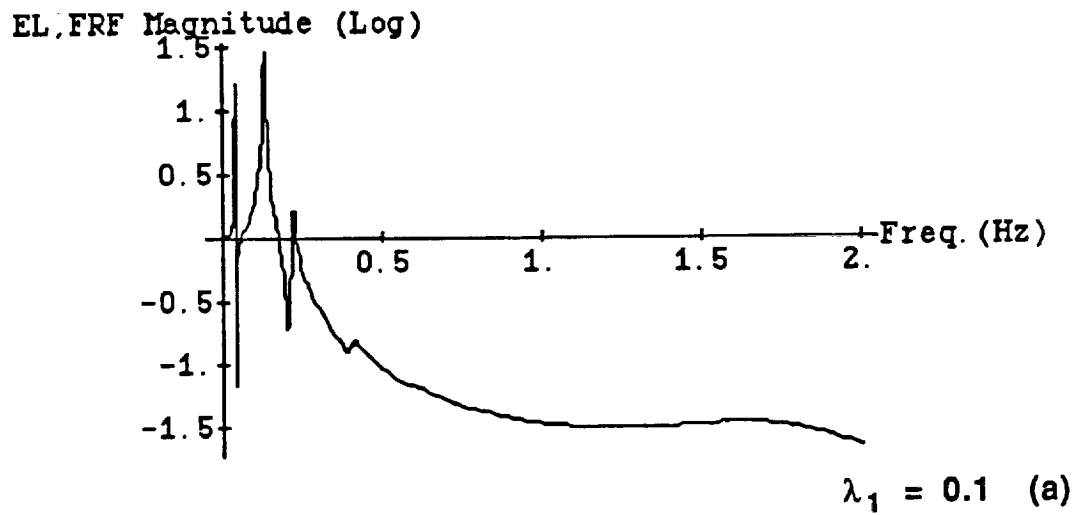
$\lambda_1 = 0.5$ (b)

EL,FRF Magnitude (Log)



$\lambda_1 = 0.9$ (c)

Figures 5(a), 5(b) and 5(c)



Figures 6(a), 6(b) and 6(c)

3. PROBLEMS ENCOUNTERED DURING REPORTING PERIOD

None

4. ACTIVITY PLANNED FOR NEXT REPORTING PERIOD

During the next reporting period we will continue the analysis of the accelerations acting on board VGL. Under Aeritalia directions, a preliminary geometric design of VGL will be used to run numerical simulations with the rotational dynamics of the elevator.